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Reliability, Availability, and Maintainability Testing of High Pressure Pumping Units for Mobile Army 600 Reverse Osmosis Water Purification Unit

by Wayne W. Sharp, Howard K. Bell Consulting Engineers, Inc.

Charles R. O'Quinn, Michael G. Channell, WES

WES

Prepared for Belvoir Research, Development, and Engineering Center

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Howard K. Bell Consulting Engineers, Inc.
P.O. Box 546
Lexington, KY 40585

Charles R. O'Quinn, Michael G. Channell

U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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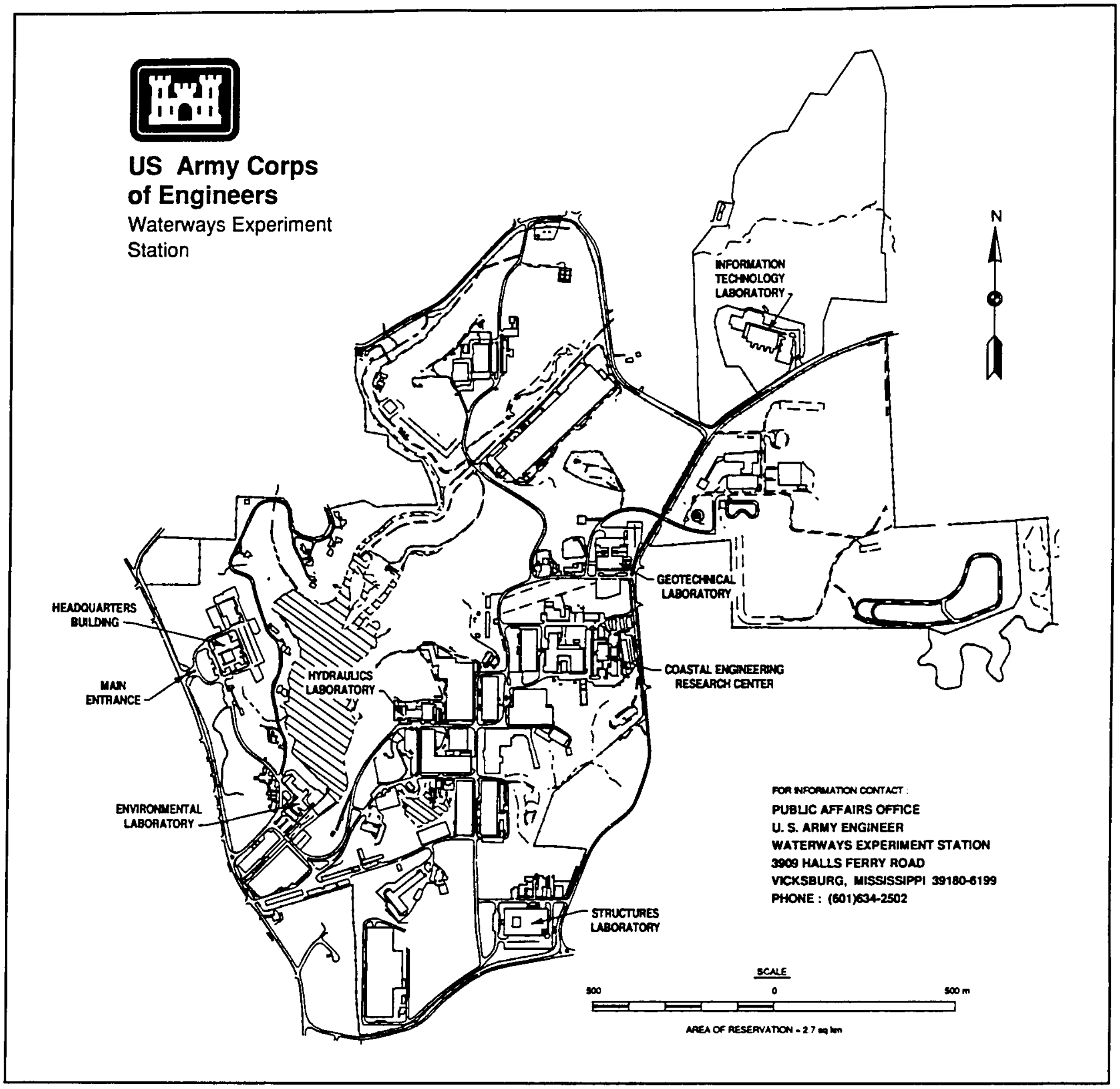

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Preface

The report herein describes testing procedures and results applicable to reverse osmosis water purification high pressure pumping units. This work was sponsored by the Department of Army, Belvoir Research, Development, and Engineering Center, Fort Belvoir, VA. The technical monitor for this work was Mr. Bob Shalowitz.

The work was conducted by the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS. The test facility for reliability, availability, and maintainability testing was located at the U.S. Army Engineer District, Vicksburg, Harbor Project. This report was written by Mr. Wayne W. Sharp, Howard K. Bell Consulting Engineers, Inc., and Mr. Charles R. O'Quinn, Engineering and Construction Services Division, WES, and Mr. Michael G. Channell, Environmental Restoration Branch (ERB), Environmental Engineering Division (EED), Environmental Laboratory (EL), WES.

Mr. O'Quinn was responsible for the physical operations and construction of the test facility and daily data collection during all test phases at the Harbor Project. At the time of testing, Mr. Douglas Lee was plant supervisor at the Harbor Project.

Electronic data collection during start-up testing was provided by Messrs. Joe Savage, Leo Koestler III, and Richard Floyd, Instrumentation Services Division, WES.

Scanning electron microscope testing and results were reported by Messrs. Jerry P. Burkes and Sam Wong, Structures Laboratory, WES.

The study was conducted under the supervision of Mr. Norman R. Francingues, Chief, ERB; Dr. Raymond L. Montgomery, Chief, EED; and Dr. John W. Keeley, Director, EL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
Fahrenheit degrees	5/9	Celsius degrees or kelvins[1]
feet	0.3048	meters
gallons (U.S. liquid)	3.785412	liters
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
pounds (force) per square inch	6.894757	kilopascals
quarts (U.S. liquid)	0.9463529	liters

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9) (F - 32). To obtain kelvin (K) readings, use the following: K = (5/9) (F - 32) + 273.15.

1 Introduction

Background

Mobile reverse osmosis water purification units (ROWPUs) are used by the Army for production of potable water, particularly from saline, brackish, and fresh sources. Figure 1 shows the Mobile Army 600 gal/hr[1] ROWPU. The reverse osmosis is a membrane process requiring a high pressure (up to 1,000 psi) feed stream. Therefore, a high pressure pump is a key ROWPU component. The work described in this report involves testing high pressure pumps from various vendors to evaluate their use as ROWPU components.

Pressure

This report provides data obtained by a unified testing program applicable to all high pressure pumping units that are candidates for use as ROWPU components. The testing program consists of three test phases (initial inspection, start-up testing, and endurance testing) to assess the following pumping unit characteristics ("pumping unit" refers to a pump-motor-pulsation damper combination):

a. Physical dimensions and weight.

b. Noise generation data.

c. Acceleration (vibration) data.

d. Operational characteristics (flow rate and pressure delivered).

e. Reliability.

f. Availability.

[1] A table of factors for converting Non-SI units of measurements to SI units is presented on page vii.

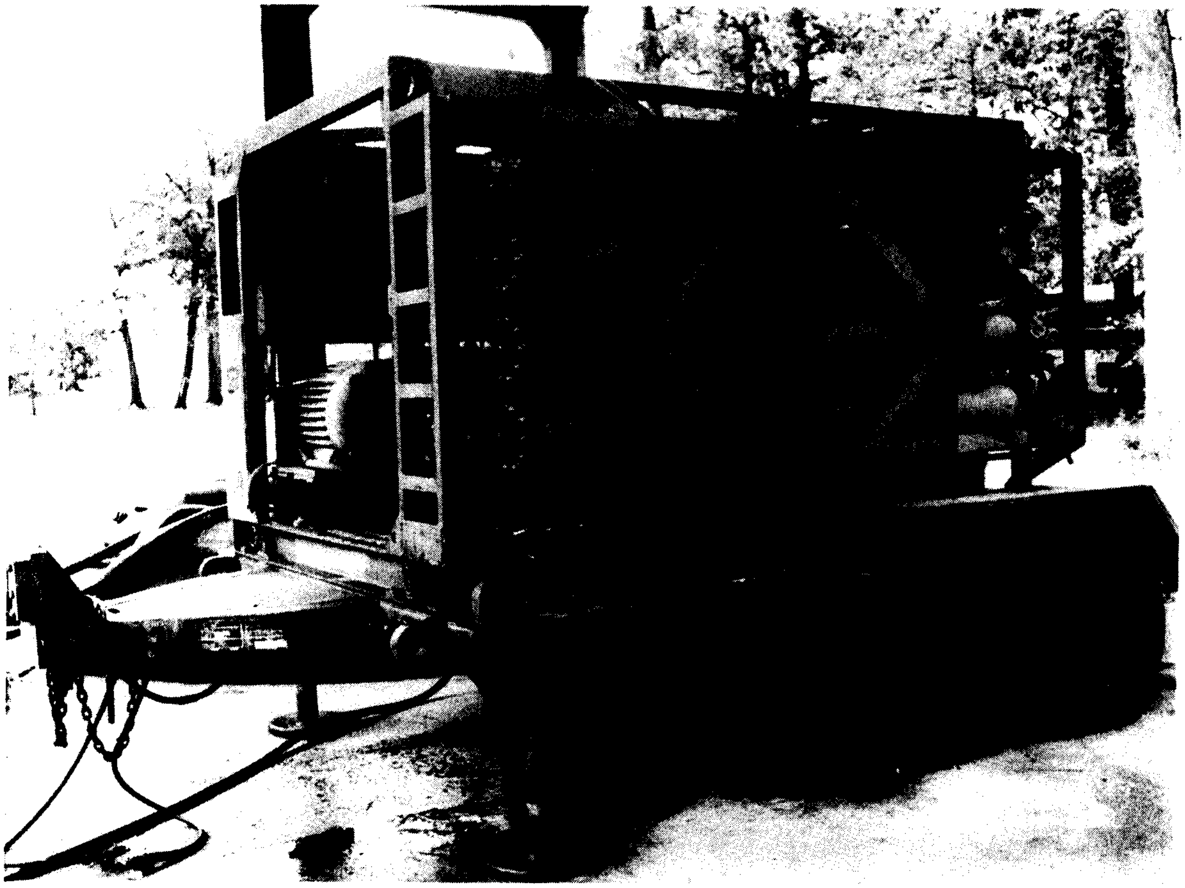


Figure 1. Mobile Army 600 ROWPU

g. Maintainability.

h. Compatibility with ROWPU.

Test procedures are described in Chapter 4. Results from all test phases are presented in Chapter 5.

2 Pumping Unit Characteristics

A general description of each pump and motor evaluated is presented in Table 1. All pumps were selected to deliver 60 gal/min at 1,000 psig. All motors were supplied three-phase, 60-Hz, 460-V electrical service. A motor control center common to all pumping units was utilized for electrical control. The manufacturer's off-the-shelf manuals (not included in this report) were utilized for installation, operation, and repairs.

Table 1
Pump and Motor Description

Pump (Model)	Motor	Hp	Drive	Inlet NPT	Outlet NPT	Length in. (Pump and Motor)	Width in. (Pump and Motor)	Height in.	Weight lb
Wheatley Quintuplex	General Electric	40	Belt	3 in.	1.5 in.	40.0	32.25	46.0	1,663
Union TD 30 Triplex	Duty Master	40	Belt	2 in.	1.5 in	59.75	35.75	35.50	1,572
Sundstrand Sunflo P-2000	Marathon	75	Shaft	2 in.	1.5 in.	48.0	18.0	19.5	640
FMC L11	U.S. Electric	40	Belt	2.5 in.	1.25 in.	32.31	20.25	14.31	855
Ingersoll Rand HDP-31 (Hammellman)	Lincoln	40	Belt	2 in.	1.5 in.	59.58	30.63	41.50	900

Note: NPT = National Pipe Threads.

A pulsation damper located immediately downstream of the pump absorbs pressure surges and protects reverse osmosis (RO) elements. Dampers used during testing are identified in Table 2. Pumping unit selection was made by the U.S. Army Belvoir Research, Development, and Engineering Center (BRDEC).

Table 2
Pulsation Damper Description

Model	Overall Length in.	Outside Diameter in.	Mechanism
Young Engineering (Zemark)	36	12	Reservoired stainless steel acoustical
White Rock	24	12	Reservoired stainless steel acoustical
Greer	16	10	1-qt Bladder - nitrogen charged
Greer	10	7	4-qt Bladder - nitrogen charged

3 Facility Design

The ROWPU test facility was constructed in an outdoor shelter (roof and back wall only) located at the U.S. Army Engineer District, Vicksburg, Harbor Project, Vicksburg, MS. Figure 2 shows the test facility design. The facility was constructed on a poured concrete pad and fenced on all open sides with access gates.

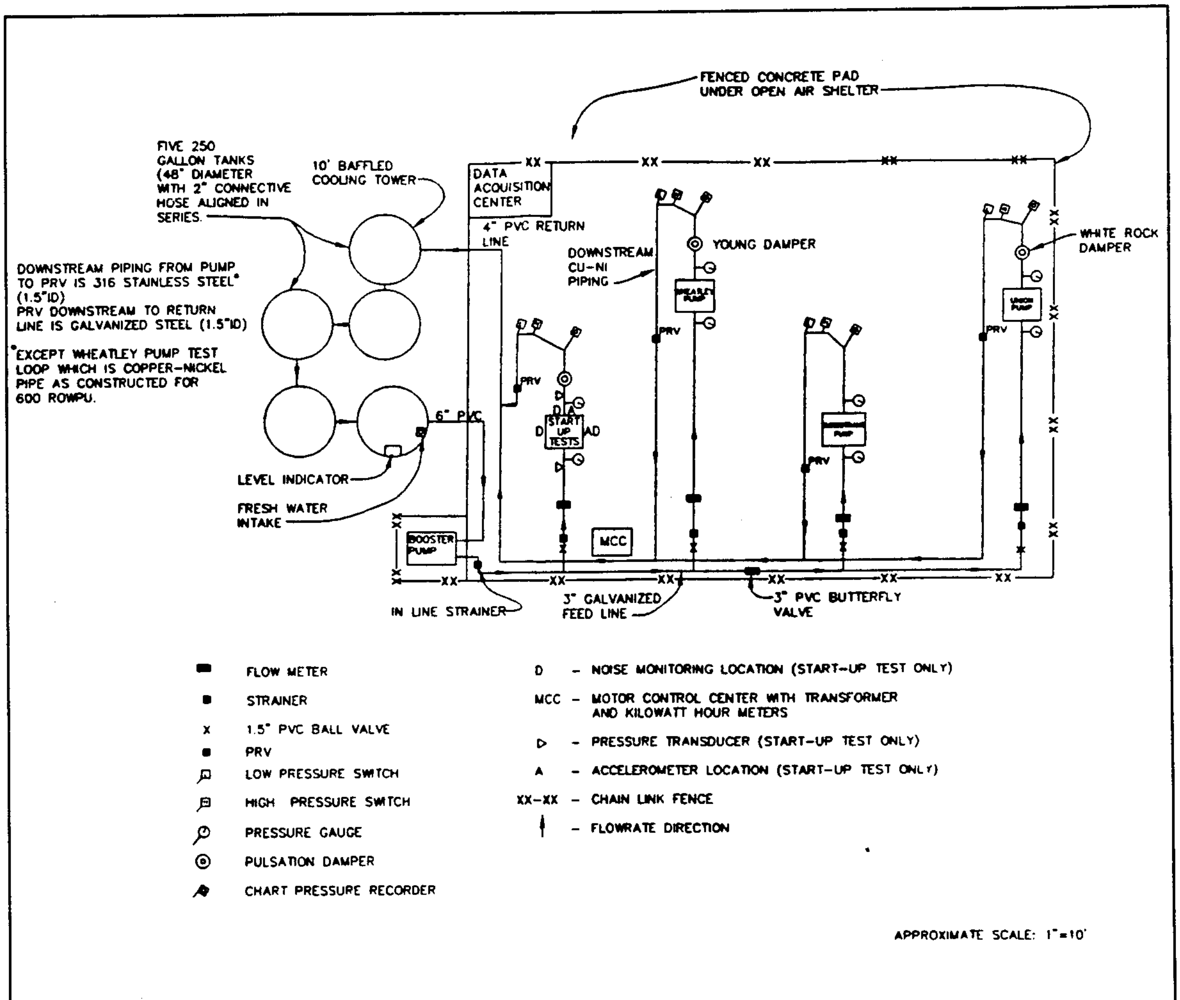


Figure 2. Test facility plan view

The test fluid was a saltwater solution composed of bulk salt dissolved in potable water to create a saline solution between 1.5 and 3.0 parts per thousand. Five 250-gal, coated steel tanks served as the test fluid reservoir. One tank was converted into a fan-driven cooling tower to help dissipate the heat transferred into the test fluid from the high pressure pumping loops. A freshwater intake was also designed to replace lost fluids because of system leaks and evaporation. A liquid level switch was installed in the reservoir to completely shut off power in the event of fluid loss to protect the pumping units.

A booster pump designed to deliver 60 gpm at 42 psig and 180 gpm at 32 psig was installed downstream of the reservoir. This booster pump supplied the tested pumping units with the required net positive suction head. An in-line strainer downstream of the booster pump provided protection to the pumping units and associated appurtenances.

Four test loops were constructed to accommodate start-up and endurance testing requirements (Chapter 4). Individual test loops include a strainer for debris removal, high and low pressure switches to cut power to individual motors for personal and mechanical safety, pressure gauges to manually monitor suction and discharge conditions, a pressure-regulating valve to control discharge pressure from the pumping units, ball valves, unions, and necessary fittings to meet data acquisition requirements. Discharge piping was configured to approximate the shape and length of the Mobile Army 600 ROWPU. All discharge piping was constructed of 1.5-in. (inside diameter) NPT, 316 stainless steel rated at 1,200 psig with one exception. Copper-nickel piping (90-10) as constructed for the Mobile Army 600 ROWPU was installed in one endurance test loop for materials-testing purposes.

The start-up test loop was constructed to allow the potential for 25 pumping unit combinations to be tested. Flexible, high pressure hoses were utilized to make the necessary attachments between suction and discharge piping, pulsation damper, and pump for each pumping unit combination. A data acquisition structure with heating and air conditioning was installed to protect and house the electronic equipment (computers, oscilloscopes, etc.) necessary to acquire start-up test data. Pressure transducers and accelerometers were installed to measure pressure differentials and mechanical vibrations, respectively.

The endurance test loops (three total) were constructed for the individual pumping unit to be tested and are less data intensive. Design priorities were established for access ease and maintenance considerations. Data acquisition for endurance testing was manual (not electronic). Chapter 4 details data requirements for both start-up and endurance testing.

The test facility was powered by Mississippi Power and Light Company. Initiating from a 13,800-V service, two transformers stepped down the supply voltage to the 230/460-V service required for testing purposes. All motors

were supplied a 460-V, three-phase, 60-Hz service. All lighting, safety switches, data acquisition equipment, etc., utilized an existing 115-V service.

A motor control center (MCC) was installed to electrically control the test facility. All pumping units and related controls (pressure switches and liquid level switch) were governed through the MCC. All electrical data (amperage and kilowatt hour) were obtained through equipment installed in the MCC. The timer installed for endurance testing was housed in the MCC where the individual starters to each pumping unit could be controlled.

4 Testing Procedures

Initial Inspection

Initial inspection involved disassembling and visually inspecting pumping unit components. Components that were inspected included valves, packings, bearings, crankshaft, belts, driver, exterior of unit, pulsation damper, and skid. All information presented in Tables 1 and 2 was verified or determined during initial inspection. Initial inspection also allowed testing personnel to familiarize themselves with the pumping units. Disassembly of the pumps and pulsation dampers was done in strict accordance with the manufacturer's off-the-shelf manuals.

Start-up Testing

Start-up testing included an extensive collection of electrical, fluid, vibration, and noise data for each possible combination of five pumps and four dampers as well as no damper (25 possible combinations).

Each pumping unit combination was installed in the start-up test loop (Figure 2) and operated under similar conditions for a 6-hr period. The following data were obtained for each pumping unit tested.

a. Temperature and salinity of test fluid.

b. Start-up amperage (instantaneous peak).

c. Operating amperage at 1,000 psi, 60 gpm.

d. Suction pressure (Appendixes A-D).

e. Discharge pressure (Appendixes A-D).

f. Vertical acceleration on pump frame and floor.

g. Horizontal acceleration on pump frame and floor.

h. Noise levels (db).

i. Flow rate.

Temperature and salinity of the test fluid were recorded before initiating each test. Start-up and operating amperage readings were obtained through the MCC. Each pumping unit was started at maximum test pressure (1,000 psig) a minimum of four times to obtain the average start-up (instantaneous peak) amperage required. Operating amperage was obtained multiple times throughout each 6-hr test.

Suction and discharge pressures were obtained manually and electronically. Manual readings from 4-in. dial, fluid-dampened pressure gauges mounted on both the suction and discharge side of the pump gave visual indication to the tester and allowed proper pressure regulating valve (PRV) adjustment to ensure proper operation of the pumping unit. Transducers, installed flush-mounted with inside walls of suction and discharge piping, electronically recorded (820 readings per second) suction and discharge pressures (after the pulsation damper if applicable). These readings were recorded for a 15-min duration of each pumping unit test. These pressure readings help quantify the effects of the pulsation damper.

Vibration data were obtained by the use of accelerometers mounted on the pump frame and on the concrete pad to which the pumping unit was anchored. Four 7/8-in. by 3-in. concrete anchors bolted through the mounting brackets on the skid were used. A polypropylene pad 3/8-in. thick separated the pumping unit from the concrete pad. These accelerometer readings quantify the mechanical vibrations caused by the pumping unit. This data were recorded for a 15-min duration of each pumping unit test.

Noise levels for each pumping unit were obtained by a hand-held decibel meter. Three locations, each 2.0 ft (horizontally) from the pump frame and 3.0 ft (vertically) from the pad, were used to obtain an average noise level (db) for each pumping unit.

Flow rate produced by each pumping unit was verified by an in-line disk flowmeter. All pumping units tested delivered 60 gpm at 1,000 psig.

Data obtained from start-up testing are presented in Chapter 5.

Endurance Testing

At the conclusion of the start-up testing, three pumping units were selected for endurance testing by U.S. Army Engineer Waterways Experiment Station (WES) and BRDEC personnel, based on start-up test results. The selected pumping units were installed in parallel in the test loop and operated by a mechanical timer, to provide approximately 60 gpm at 1,000 psi for 20 hr per day, 7 days a week, until a total of 2,000 hr of operation were reached, or a

failure event necessitated cessation (Figure 2). Pumping units were operated and maintained in strict accordance with manufacturer's off-the-shelf manuals. Efforts were made to confine routine and preventive maintenance to the 4 hr of daily scheduled downtime. A daily log was kept for each pump unit being tested, and the following parameters were recorded daily:

a. Suction pressure.

b. Discharge pressure.

c. Flow rate.

d. Fluid temperature and salinity.

Suction and discharge pressures were obtained manually from 4-in. dial, fluid-dampened pressure gauges. Chart recorders were utilized to obtain a continuous record of discharge pressure for each pumping unit.

These records helped to indicate failure scenarios during periods when no testing personnel were on site.

All pumping units were operated at 1,000 psig (±50 psig) discharge pressure controlled by the downstream pressure regulating valve. The suction pressure supplied to each pumping unit was 32 psig (±2.5 psig) from the booster pump.

The flow rate produced by each pumping unit was measured by a dedicated disk flowmeter (accumulator). All pumping units delivered 60 gpm at 1,000 psig. Fluid temperature and salinity were recorded daily.

Power consumption for each pumping unit was recorded daily from a dedicated kilowatt hour meter located at the motor control center. Increasing power consumption during testing could indicate decreasing efficiencies.

Failures during endurance testing were defined as any malfunction that caused or may cause inability to commence operation, cessation of operation, degradation of performance below designated levels, or serious personnel safety hazards.

Any malfunction that the operator could remedy was not considered a failure provided that the repair was authorized or prescribed as an operator function and could be accomplished in 30 min or less using only controls and small hand tools. Whenever a pumping unit failure occurred, the time, nature, and cause of the failure was documented. Pumping unit reliability, availability, and maintainability (RAM) were examined and quantified.

In conjunction with the RAM endurance tests, copper-nickel (Cu-Ni) piping was utilized on the discharge side of the Wheatley pump test loop. This piping was procured from MECO, Inc., manufacturer of the Mobile Army

600 ROWPU, and is nearly identical to the discharge piping used in the 600 ROWPU. Additional 1/4-in. NPT parts were manufactured into the pipe assembly to meet endurance test equipment requirements (pressure gauges, etc.). Two complete assemblies were procured, such that used and unused pipe could be evaluated for ROWPU compatibility upon completion of RAM endurance testing. A scanning electron microscope was used to quantify corrosion and corrosion products in the Cu-Ni pipe. Appendix E documents the findings from this investigation.

5 Test Results

Initial Inspection

The following observations were recorded during the initial inspection for each pump and pulsation damper. Tables 1 and 2 list overall characteristics verified by initial inspection. All units were disassembled and inspected within 90 days of arrival.

a. Wheatley Pump (Figure 3).

(1) Pump was disassembled easily in accordance with the manufacturer's off-the-shelf manual.

(2) Fluid end was free of standing water.

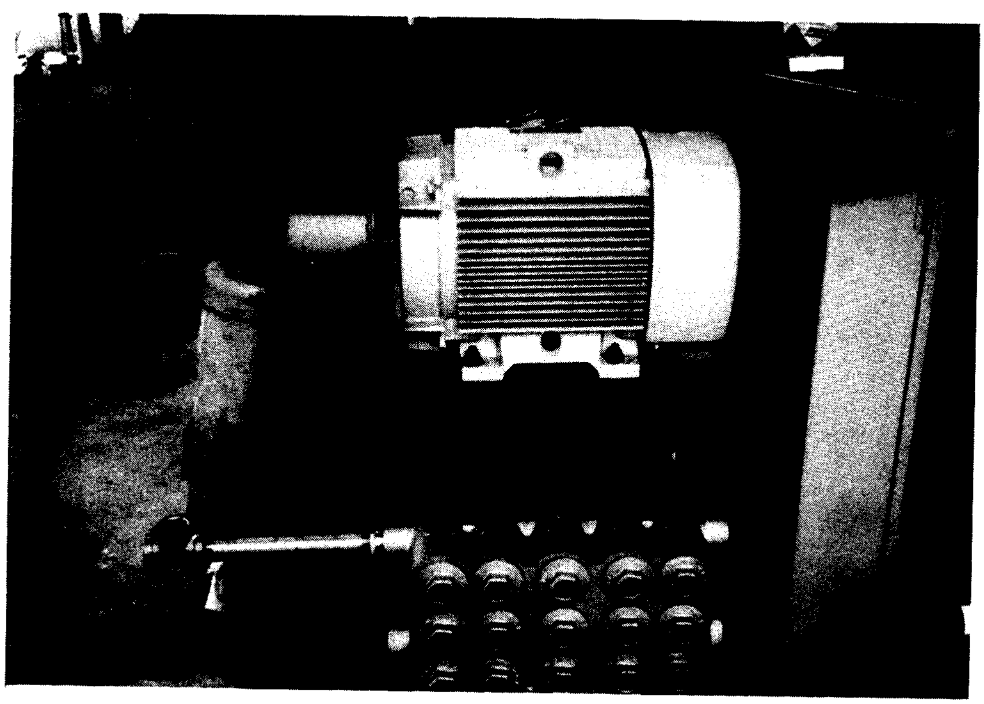


Figure 3. Wheatley quintuplex pump

(3) Internal materials appeared in good condition, and all parts including the crankshaft were easily accessible.

(4) Valves, packings, crankshaft, belt, coupling, driver, and pump exterior were in good shape.

(5) Bearings were burred and scratched. Metal shavings were observed in the oil reservoir and removed with a magnet.

b. Union Pump (Figure 4).

(1) Pump was disassembled easily in accordance with the manufacturer's off-the-shelf manual.

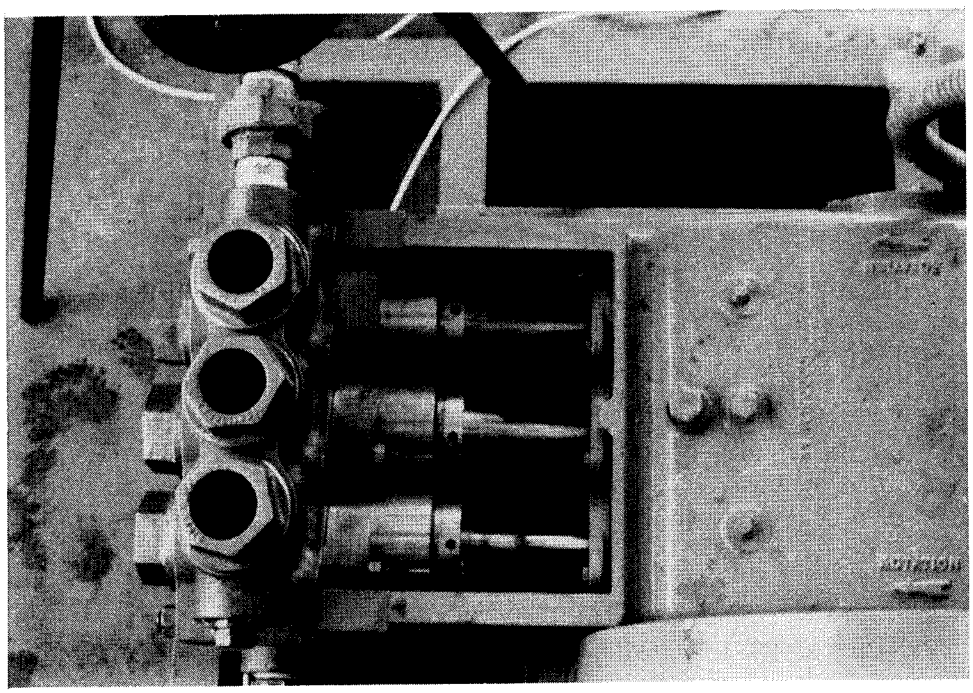


Figure 4. Union pump fluid end

(2) Rust was forming on cast iron surfaces around plunger on the liquid end of the pump.

(3) Water was retained in the liquid end of the pump even with plug extracted.

(4) Rust was forming on valves, couplings, driver, and on the exterior of the pump.

(5) Packings, crankshaft, and belts appeared to be in good condition.

c. Sundstrand Pump (Figure 5).

(1) Pump was disassembled very easily in accordance with the manufacturer's off-the-shelf manual. Compared with the positive displacement pumps, there are less moving parts, and disassembly/reassembly was easier.

Figure 5. Sundstrand pump (Greer 4-qt damper)

(2) No rust was apparent internally or externally.

(3) Entire pump unit (as a whole) was easily removed.

(4) Impellers, gears, and exterior of the pump were in excellent shape.

d. Ingersoll-Rand (Hammellman) Pump (Figure 6).

(1) Pump was easily disassembled in accordance with the manufacturer's off-the-shelf manual.

(2) No rust was apparent on internal or external surfaces.

(3) A slight tear was apparent in the center cylinder rubber packing.

(4) Crankshaft was difficult to access—motor was removed to access.

(5) Packings, valves, pistons, belts, coupling, driver, and exterior of the pump were in good condition.

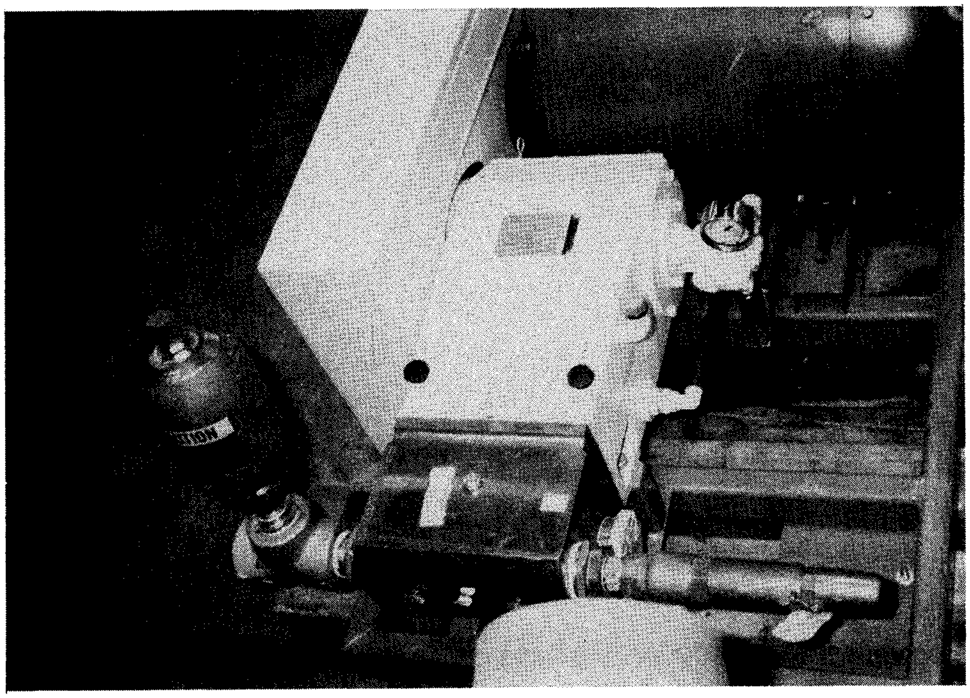


Figure 6. Ingersoll Rand pump (Greer 1-qt damper)

e. FMC Pump (photo not available). The FMC pump was not initially inspected because of its late arrival.

f. Pulsation Dampers.

(1) The White Rock damper (Figure 7) is a cylindrical, stainless steel, acoustical damper. It is the heaviest damper, but not the largest. Infeasible to disassemble.

(2) The Young Engineering damper (Figure 8) is a cylindrical, stainless steel, acoustical damper. It is the largest damper. Infeasible to disassemble.

(3) The Greer 1-qt and Greer 4-qt bladder dampers were disassembled according to the manufacturer's off-the-shelf manual. The 4-qt (1-gal) model was found to be in good condition internally and externally. Both models require a compressed gas (nitrogen) precharge before use.

(4) The Greer 1-qt bladder was damaged upon inspection. The manufacturer could not supply additional bladder in the necessary time frame (2 weeks). Thus, the Greer 1-qt pulsation damper was eliminated from further testing.

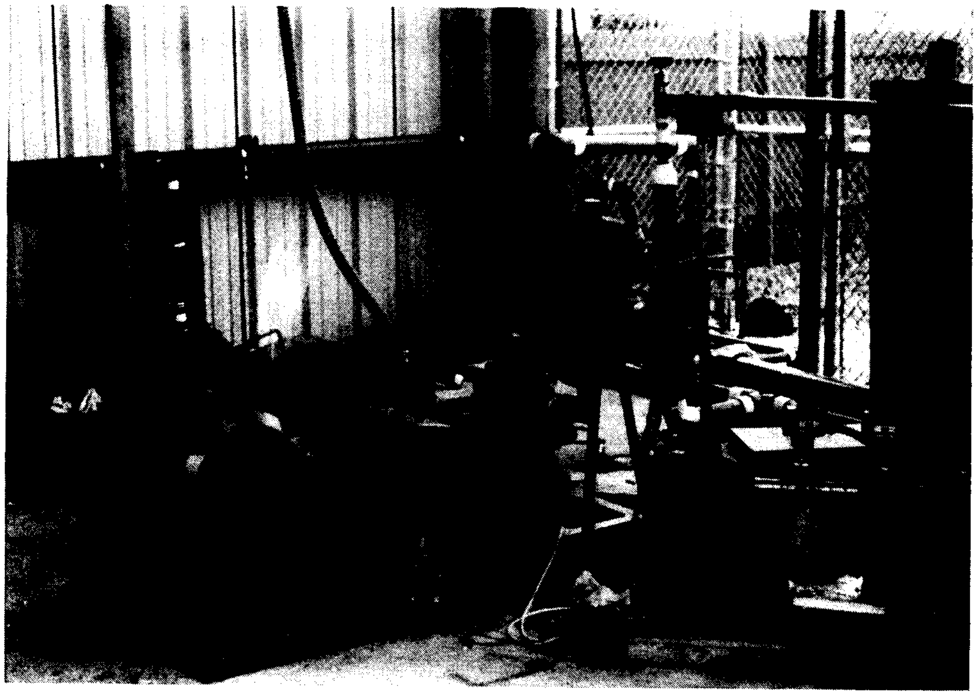


Figure 7. White Rock damper (Union pump)

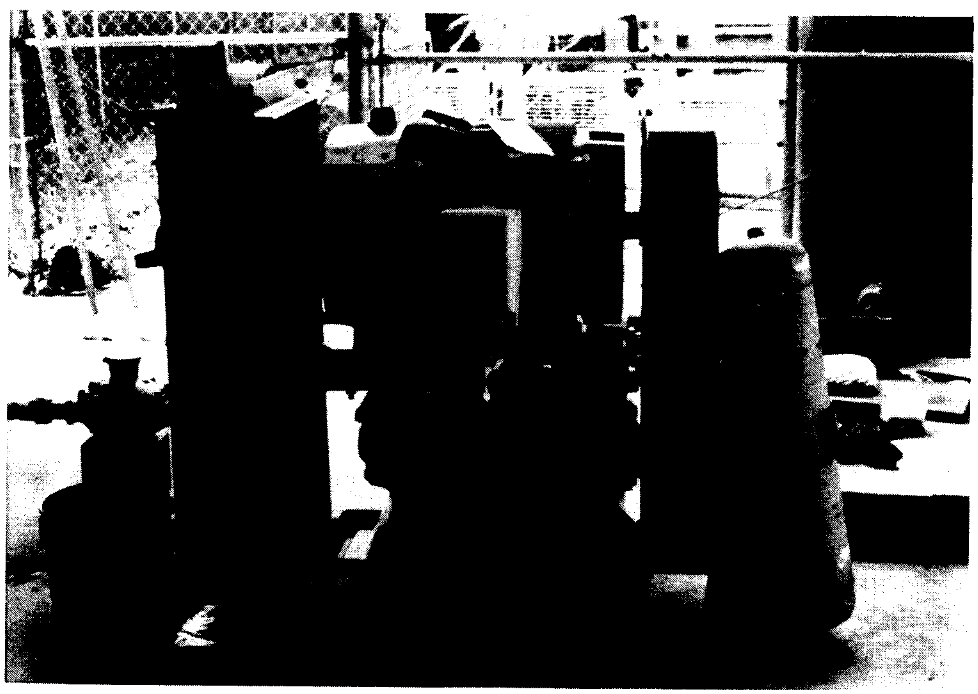


Figure 8. Young Engineering damper (Wheatley pump)

Start-up Testing

Start-up tests were conducted as described in Chapter 4. The Ingersoll-Rand pump experienced mechanical problems with valves sticking in the pump, rendering the pump inoperable. The pump was disassembled, the intake valves were shaved according to the manufacturer's off-the-shelf manual and Ingersoll-Rand personnel, and the pump remained inoperable.

Start-up testing proceeded with the other pumping units. A total of 16 combinations remained to be tested (four pumps, four pulsation dampers). The following data summarize start-up test results from these 16 pumping unit combinations. All pumping units tested delivered 60 gpm at 1,000 psig successfully.

Start-up and operating amperage

Start-up and operating amperage readings were obtained from the MCC (460-V) for each pumping unit combination starting and operating at 1,000 psig and 60 gpm. A minimum of four recordings were obtained for each combination, and the average of these readings is shown in Table 3.

Table 3
Average Start-up and Operating Amperage

		Amperage (amps)	
Pump Model	**Damper**	**Start-up**	**Average Run**
Wheatley	White Rock	190	38
	Young	200	33
	Greer	210	37
	None	190	38
Union	White Rock	190	40
	Young	200	41
	Greer	205	40
	None	190	39
Sundstrand	White Rock	416	80
	Young	416	77
	Greer	416	80
	None	416	80
FMC	White Rock	260	39
	Young	260	40
	Greer	250	40
	None	260	40

Starting the pumping units at 1,000 psig created a current (amperage) demand 500 to 625 percent greater than normal operating amperage. Given all pulsation damper combinations, the Union pump averaged approximately

500-percent increase. The FMC pump was highest, averaging an approximate 625-percent increase.

The Sundstrand pump requires twice as much amperage to operate because of its 75-hp motor, which is nearly twice as large as the other pumps and half as efficient.

Suction and discharge pressure

Suction and discharge pressures were recorded 820 times per second with pressure transducers for each pumping unit combination. These results help quantify the effects of the different pulsation dampers with each pump. Appendixes A-D, respectively, show a 0.5-sec recording of suction and discharge pressures for each pumping unit combination (Appendix A is the Wheatley pump combinations; Appendix B is the Union pump combinations; Appendix C is the Sundstrand pump combinations; Appendix D is the FMC pump combinations). Table 4 summarizes information from Appendixes A-D. The maximum, minimum, average, and change in pressure delivered by each pumping unit is shown.

Table 4
Suction and Discharge Pressures

		Pressure, psi							
		Discharge				Suction			
Pump Model	Damper	Maximum	Minimum	Average	ΔP	Maximum	Minimum	Average	ΔP
Wheatley	White Rock	1,064	997	1,036	67	78	31	47	47
	Young	1,102	1,015	1,060	88	91	40	57	50
	Greer	1,123	1,001	1,058	123	77	37	43	41
	None	1,148	898	1,063	250	68	23	38	45
Union	White Rock	1,085	1,020	1,056	66	94	29	27	65
	Young	1,089	1,008	1,047	81	107	43	25	64
	Greer	1,116	925	1,041	192	126	-13	27	138
	None	1,167	906	1,045	262	143	-8	32	151
Sund-strand	White Rock	1,057	1,025	1,041	32	36	17	26	19
	Young	1,079	1,044	1,060	35	77	54	65	23
	Greer	1,047	1,014	1,029	34	68	47	56	22
	None	1,061	1,020	1,040	41	30	15	23	15
FMC	White Rock	1,115	1,036	1,080	79	89	-16	24	106
	Young	1,067	1,001	1,036	67	114	7	45	107
	Greer	1,097	1,034	1,063	64	111	6	44	105
	None	1,231	906	1,093	325	115	4	41	111

Evaluation of the change in pressure for each pumping unit with a pulsation damper and without a pulsation damper shows significant decreases in discharge pressure surges can be obtained with the use of a pulsation damper. However, Sundstrand pump performance was not significantly affected by any pulsation damper and was generally 50 percent less than all other pumping units with pulsation dampers (35 psig compared with 70 psig). Suction pressure surges did not seem to be significantly affected by pulsation dampers.

Vertical and horizontal acceleration (vibration)

Vibration data were obtained electronically in the vertical and horizontal directions by accelerometers located in two positions: (a) on the pump skid and (b) on the floor immediately below the pump skid. Figure 9 shows these locations on the Wheatley pump. Appendixes A-D also show a 0.5-sec recording of horizontal and vertical accelerations on the pump and floor for each pumping unit tested except the Sundstrand. Only acceleration data from the floor position were obtained for the Sundstrand pump because of the absence of a skid for the pump. Table 5 summarizes information from Appendixes A-D. Acceleration is given in gravity force equivalents (G's).

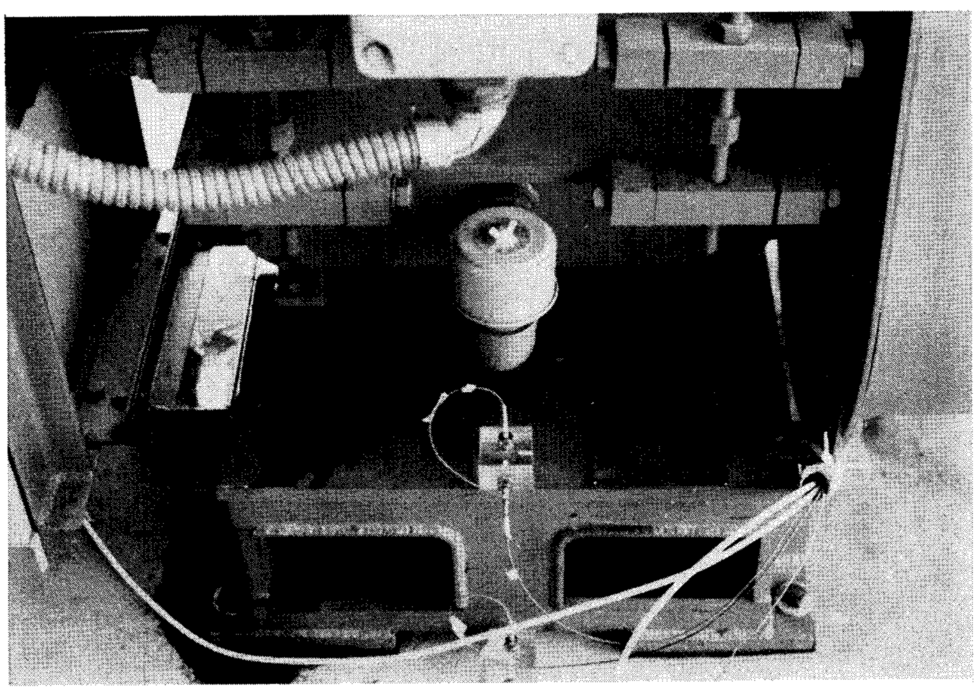


Figure 9. Accelerometer locations (start-up tests)

Based on the Table 5 data, generally, accelerations appear independent of the presence or type of pulsation damper. The Union pump tested significantly lower (several hundred percent) for acceleration data obtained from the skid (and thus the floor). The Sundstrand pump accelerations were also significantly lower based on the floor-mounted accelerometer data.

Table 5
Acceleration/Vibration Test

Pump Model	Damper	Acceleration, G's							
		Vertical on Skid		Horizontal on Floor		Vertical on Floor		Horizontal on Floor	
		Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
Wheatley	White Rock	17.5	-18.7	8.1	-9.0	0.8	-1.0	0.5	-0.5
	Young	16.3	-16.6	8.3	-7.4	1.0	-1.2	0.5	-0.6
	Greer	17.5	-15.8	8.9	-8.4	1.1	-0.9	0.5	-0.4
	None	13.7	-15.2	7.6	-8.7	0.9	-0.7	0.5	-0.5
Union	White Rock	4.0	-4.3	3.6	-4.0	0.2	-0.3	0.1	-0.1
	Young	3.3	-3.5	3.4	-2.9	0.2	-0.2	0.2	-0.1
	Greer	1.8	-1.7	2.3	-2.7	0.3	-0.3	0.1	-0.1
	None	5.5	-5.2	6.1	-6.3	0.4	-0.3	0.2	-0.2
Sund-strand	White Rock	N/A	N/A	N/A	N/A	0.9	-0.9	0.4	-0.3
	Young	N/A	N/A	N/A	N/A	0.6	-0.6	0.2	-0.3
	Greer	N/A	N/A	N/A	N/A	0.6	-0.6	N/A	N/A
	None	N/A	N/A	N/A	N/A	0.7	-0.6	0.3	-0.4
FMC	White Rock	14.8	-17.9	19.0	-18.0	N/A	N/A	1.0	-1.0
	Young	12.9	-14.0	15.7	-15.3	1.1	-1.1	N/A	N/A
	Greer	12.3	-10.3	14.5	-16.2	1.5	-1.4	1.2	-1.2
	None	8.8	-9.0	9.7	-11.2	1.3	-1.2	0.8	-0.8

Noise level

Decibel (db) readings were taken at three locations, 2 ft horizontally and 3 ft vertically from the bottom of the pumping unit. Reference can be made to Figure 2 for the locations of noise level readings. Table 6 summarizes average noise level readings for all pumping units tested.

All pumping units tested approximately 90 db. The Wheatley pump was the loudest, averaging nearly 97 db. Noise levels appear to be independent of the presence or type of pulsation damper used.

Table 6
Noise Level

Pump Model	Damper	Average Decibel Reading, db
Wheatley	White Rock	98
	Young	97
	Greer	96
	None	96
Union	White Rock	91
	Young	81
	Greer	92
	None	
Sundstrand	White Rock	88
	Young	93
	Greer	89
	None	88
FMC	White Rock	91
	Young	89
	Greer	90
	None	90

Temperature and salinity

The temperature and salinity of the test fluid at the start of each pumping unit test is summarized in Table 7. Test fluid temperatures rose to approximately 35 to 40 °C for all pumping units after approximately 6 hr of continuous operation.

Table 7
Temperature and Salinity at Beginning of Test

Pump Model	Damper	Salinity, %	Water Temperature, °C
Wheatley	White Rock	3.0	13
	Young	3.0	6
	Greer	2.7	15
	None		
Union	White Rock	2.8	9
	Young	2.9	5
	Greer	2.6	16
	None	2.7	16
Sundstrand	White Rock	2.1	6
	Young	1.5	13
	Greer	2.3	17
	None	2.1	3
FMC	White Rock	2.2	20
	Young	2.2	4
	Greer	2.0	7
	None	1.9	3

Start-up test summary and endurance test pumping unit selection

Based on results from the initial inspection and start-up tests, three pumping units were selected for endurance testing.

Given acceptable test results from the four pumps tested during start-up tests, the Ingersoll-Rand pump, experiencing valve problems, was eliminated as a candidate for endurance testing.

The FMC pump experienced significant leaking around the leather packing in one of the cylinders from the onset of start-up testing. The packing was removed, reassembled, allowed to soak (leather packings swell and seal), and continued to leak for the duration of start-up testing. All other pumps tested performed acceptably. Given this situation and the qualitative assessment that the FMC pump neither tested superior or inferior to the other pumps according to the data obtained during start-up testing, the FMC was eliminated as a candidate for endurance testing.

The three pumps to be used during endurance testing were then defined: Union, Wheatley, and Sundstrand.

Based on data presented in Table 4 concerning pressure, the damper providing the least amount of pressure surge protection (greatest delta P) for the Wheatley and Union pumps is the Greer 4 qt. No damper is required for the Sundstrand pump. The White Rock damper showed smaller pressure surges in both the Union and Wheatley pumps than in the Young Engineering damper and thus was selected to accompany the pump exhibiting the highest pressure surge with no damper, which was the Union pump. Thus, endurance testing pumping units are defined: Union pump with White Rock damper, Wheatley pump with Young engineering damper, and Sundstrand pump with no damper.

Endurance Testing

The following pumping units were selected for endurance testing and installed in the test facility (Figure 2).

a. Wheatley pump with Zemark (Young Engineering) damper.

b. Union pump with White Rock damper.

c. Sundstrand pump with no damper.

Each pump was anchored through the manufacturer's mounting brackets with four (3-in. by 7/8-in.) concrete anchors. A 3/8-in. polypropylene pad separated each pump from the concrete pad.

Each unit was targeted to operate 20 hr per day, 7 days a week for 2,000 hr or until failures necessitated the end of testing. Daily records were kept for each pumping unit concerning all operations, including routine maintenance and failure events. Parameters such as suction pressure, discharge pressure, flow rate, test fluid temperature and salinity, and supply voltage were the same for all pumping units and are summarized below.

a. Pump suction pressure: 32 psig (manual gauge reading).

b. Pump discharge pressure: 1,000 psig (manual gauge reading).

c. Flow rate: 60 gal per min.

d. Test fluid temperature and salinity: Temperature varied with seasonal changes. However, regardless of the starting temperature, the test fluid reached a steady state temperature after approximately 3 hr of daily operation of 115 °F. The temperature remained constant for the duration of the daily test because of the cooling tower and freshwater supply. Salinity varied each day from a morning high of approximately 2.2 percent (salt added) to a low of 1.5 percent as the freshwater source coupled with system leaks lowered the salinity.

e. Supply voltage: Three phase, 60 Hz, 460 V.

Parameters such as power consumption, failure scenarios, and routine maintenance are described for each individual pumping unit.

Figure 10 displays power consumption for each pumping unit during endurance testing. The linear nature of all pumping units power consumption indicates pumping efficiencies remain constant. Wire to water efficiency for each pumping unit can be calculated from Figure 11 in the following manner:[1]

$$Hp = 1.34\ Kw \qquad (1)$$

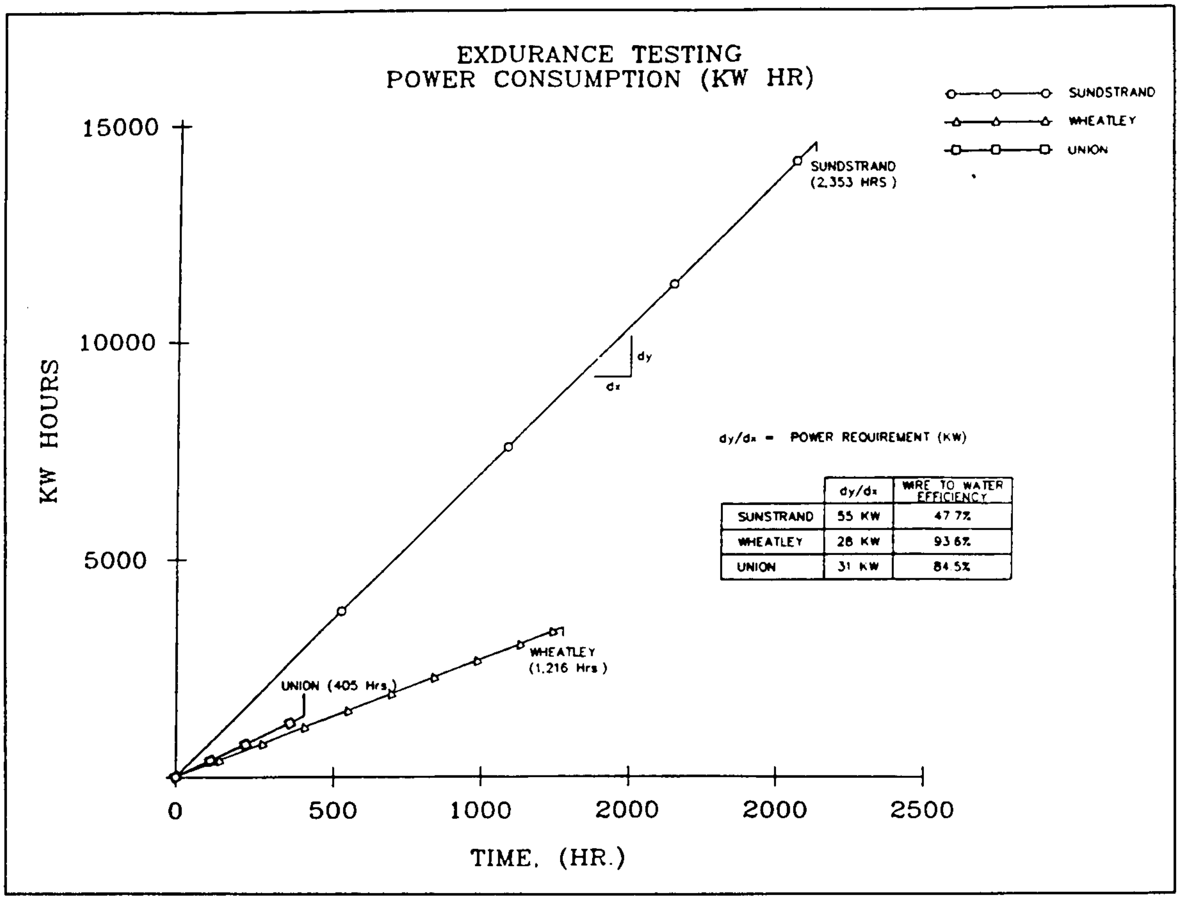
where

Hp = motor horsepower

Kw = kilowatt (power) usage (dy/dx Figure 11)

$$Hp = QH\gamma/550\ E_{w/w} \qquad (2)$$

1 Streeter, V. L., and Wylie, B. E. (1985). *Fluid mechanics.* 8th ed., McGraw-Hill, New York.



	dy/dx	WIRE TO WATER EFFICIENCY
SUNSTRAND	55 KW	47 7%
WHEATLEY	28 KW	93 6%
UNION	31 KW	84 5%

Figure 10. Power consumption during endurance testing

where

Q = delivered flow rate, cfs (60 gpm = 0.134 cfs)

H = delivered head, ft (100 psig = 2,308 ft)

γ = fluid density, lb/ft (approximately 62.4 lb/ft)

$E_{w/w}$ = wire to water efficiency

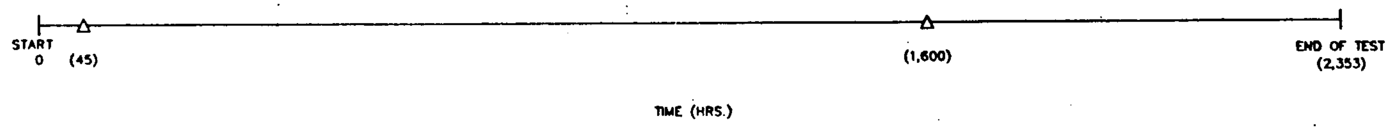
Substituting the first equation into the second, wire to water efficiency can be expressed

$$E_{w/w} = 26.185/Kw$$

This results in the following efficiencies for each pump:

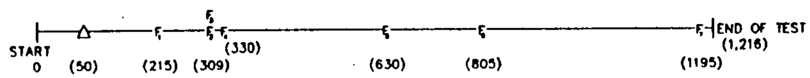
Wheatley 93.6 percent

SUNDSTRAND

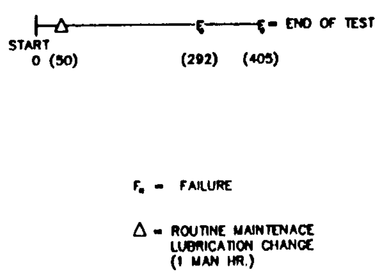


	MTBF	MR1	MR2	MR3	AI
SUNSTRAND	∞	0.005	0.0	0.005	1.0
WHEATLEY	173.7	0.016	0.029	0.044	0.972
UNION	202.5	0.041	0.020	0.016	0.976

WHEATLEY



UNION



FAILURE SUMMARY AND CORRECTIVE ACTION

F1: OIL SEAL LEAKING 3rd CYLINDER FROM SUCTION LINE. (LEAK SMALL—NO CORRECTIVE ACTION)

F2: 3 OIL SEALS FAILED: PUMP STOPPED (SEALS REPLACED)

F3: PLUNGER COATING CRACKING ON SURFACE ALLOWING RUST DEPOSITS AND IRREGULERITIES (NO NOTICEABLE SIDE EFFECTS AND NO ACTION)

F4: NEW OIL SEALS FAILED (F2) – (SEALS REPLACED)

F5: ELECTRIC MOTOR MOUNT BROKEN (MOTOR REMOVED – SURFACE REFINISHED – MOTOR MOUNTS RE-WELDED)

F6: OIL SEAL FAILURES (MIDDLE 3 CYLINDERS):(ADDING 1QT/DAY OIL)

F7: WATER LEAKS AT ALL PACKINGS: (PACKING TIGHTENED, STILL LEAK: DETERIORATED PLUNGERS (F3) CAUSED PACKINGS TO FAIL: NEW PLUNGERS AND PACKINGS REQUIRED:) TEST STOPPED (1216).

F8: NOTICEABLE KNOCKING SOUND ON CYLINDER FURTHEST FROM SUCTION LINE ACCOMPANIED BY MODERATE WATER LEAK FROM PACKING: (PACKING TIGHTENED, KNOCK PERSISTS)

F9: PISTON FAILURE – BROKEN WHERE PISTON MEETS ROD: (NEW PISTON AND ROD ASSEMBLY REQUIRED): TEST STOPPED (405) HRS.

Figure 11. Endurance test results and RAM characteristics

Union	84.5 percent
Sundstrand	47.7 percent

Figure 1 displays endurance testing results for the three pumping units tested. Failure scenarios are indicated by an upper case "F" with the hour of operational failure indicated below. Routine maintenance (oil changes) is indicated. Failure scenarios are described for each pumping unit and indicate the failure, cause of failure, remediating actions, time to repair (man-hours), availability of spare parts, and any comments about the failure.

Other parameters such as the mean time between failures (MTBF), maintenance ratios, and inherent availability are evaluated from Figure 10 and daily records. These parameters quantitatively describe the reliability, availability, and maintainability of the pumping units.

Reliability

Reliability can be defined as the probability that a product will perform a specific function under specific conditions for a stated period of time.[1] Quantitatively, reliability can be expressed as the MTBF for a particular product under specific conditions for a stated period of time. The specific conditions for the operation of the high pressure pumping units have been previously detailed; thus, MTBF can be expressed as

$$\text{MTBF} = T/n$$

where

T = total test time, hr

n = total number of failures

Maintainability

Maintainability can be defined as the probability that a failed system is restored to operable condition in a specified downtime when maintenance is performed under specified conditions. Downtime may have three components:[1]

[1] Babcock, D. L. (1991). *Managing engineering and technology*. Prentice Hall, Englewood Cliffs, NJ.

a. Administrative and preparation time.

b. Logistics time.

c. Active maintenance time.

Administrative and preparation time was not considered in this study because of the variances between testing conditions and actual field use conditions. Logistics and active maintenance times were utilized to determine the three maintenance ratios (MR) that are used to define maintainability. They are as follows:

$$MR1 = TMT/T \tag{3}$$

where

$MR1$ = total maintenance time ratio (includes routine preventive and corrective maintenance)

TMT = total maintenance time, hr

T = total test time of the pumping unit, hr

$$MR2 = CMT/T \tag{4}$$

where

$MR2$ = corrective maintenance time ratio

CMT = total corrective maintenance time, hr

T = total test time of the pumping unit, hr

$$MR3 = PMT/T \tag{5}$$

where

$MR3$ = preventive maintenance time ratio

PMT = total preventive maintenance time, hr

T = total test time of the pumping unit, hr

Availability

Availability can be defined as the probability that a system will operate satisfactorily when required. The inherent availability (Ai) of a system considers only corrective maintenance under ideal support conditions, not considering administrative or logistical delays. Inherent availability can be expressed as:[1]

$$Ai = \frac{MTBF}{MTBF + MTTR} \qquad (6)$$

where

$MTTR$ = mean time to repair (active corrective maintenance only)

RAM Results

Wheatley pump with Zemark (Young Engineering) damper

Figure 10 shows the timetable for the Wheatley pumping unit, which ran a total of 1,216 hr with seven failure events. This establishes an $MTBF$ of 173.7 hr. The seven failure events are described below:

F1 (215 hr): Oil leak in middle cylinder.
Cause: Oil seal failure.
Fix: Seal removed, inspected, and reinserted. Seal was not replaced because leak was not severe at this time.
Corrective time: 1 hr.
Availability of part: Not applicable.

F2 (309 hr): Oil leaks in middle three cylinders - Operation of pump terminated.
Cause: Oil seal failures.
Fix: All five seals removed and inspected. New manufacturer's seals ordered for all cylinders.
Corrective time: 2 hr.
Availability of parts: Parts were available and delivered to testing site within 5 working days of order.

F3 (309 hr): Plunger coating found to be cracking on two cylinders.
Cause: Unknown - Discovered only because of response to F2.
Fix: Plungers removed, inspected, and reinserted.

---

1 Babcock, D.L. (1991). *Managing engineering and technology*. Prentice Hall, Englewood Cliffs, NJ.

Corrective time: 2 hr.

Comment: At this time, there were no apparent side effects of this failure. It was ruled a failure because of the potential to cause cessation of operation. Verbal communications with the manufacturer indicated this was a known problem for this particular plunger coating. Verbal communications with BRDEC also indicated that this type of failure has been observed before on the operating Wheatley pumps.

F4 (330 hr): New oil seals exhibiting severe leaking.

Cause: Oil seal failure.

Fix: Manufacturer seals removed and nonmanufacturer seals ordered (see comment).

Corrective time: 3 hr.

Availability of parts: Seals were available for order from local retailer and were on site within 4 working days.

F5 (680 hr): Electric motor mount broken.

Cause: Structural failure at weld between motor and mount because of mechanical vibration.

Corrective time: 16 hr.

Availability of parts: Not applicable.

Comment: This was a very odd failure. Since the motor did not receive an external load at anytime during the testing, the structural failure must have been caused by fatigue because of mechanical vibration. Since the motor is mounted vertically above the pump (and thus foundation), it does seem logical that this configuration is more likely to receive higher mechanical vibration than the traditional pump/motor combination on the same horizontal plane.

F6 (885 hr): Oil seal failures in middle three cylinders (severe).

Cause: Oil seal failures.

Fix: Middle three seals removed and reinserted trying to establish new seat for existing seals.

Corrective time: 3 hr.

Availability of parts: Not applicable.

Comment: Oil leak requiring additional 1 to 2 qt of oil per day to be added for continued operations.

F7 (1,195 hr): Water leaks developing at three packing glands.

Cause: Deteriorated plunger coating on three cylinders.

Fix: New plungers and new packing assemblies needed for these three cylinders immediately and most likely on all five in immediate future. Tightening of packings was attempted and did not alleviate the problem.

Corrective time: 8 hr.

Availability of parts: Plungers and packings were available from manufacturer but not ordered.

Comment: The corrective action needed for this failure coupled with the recurring oil leaks necessitated the need to stop pump testing because of excessive repair costs and time. The corrective time of 8 hr is an estimate based on previous repair times for this pump.

Summing all the corrective times for the Wheatley pumping unit gives a total of 35 man-hours devoted to corrective maintenance. This yields a corrective maintenance time ration of the following:

$$MR2 = 35\ hr/1{,}216\ hr$$

$$MR2 = .029$$

Preventive maintenance time was found to be 19 hr (1 hr for every 63 hr of pump operation) making routine checks on all pumping unit components. This establishes a preventive maintenance time ratio of the following:

$$MR3 = 19\ hr/1{,}216\ hr$$

$$MR3 = 0.016$$

Total maintenance time is the sum of preventive and corrective maintenance, which is 54 hr. This yields a total maintenance time ration of the following:

$$MR1 = 54\ hr/1{,}216\ hr$$

$$MR1 = 0.044$$

The *MTTR* is the total corrective maintenance hours (35) divided by the number of failures (7). Thus, *MTTR* = 5.0 hr. The *Ai* is established as follows:

$$Ai = \frac{173.7}{(173.7 + 5)}$$

$$Ai = 0.972$$

Union pump with White Rock damper

Figure 11 shows the timetable for the Union pumping unit, which ran for a total of 405 hr with two failure events. This establishes an *MTBF* of 202.5 hr. The two failure events are described below.

F8 (292 hr): Knocking sound on cylinder farthest from suction end accompanied by moderate water leak from packing.

Cause: Largely unknown, but suspected to be first signs of improper alignment between power and fluid ends.

Fix: Alignment was checked according to manufacturer's operations manual; adjustments were not deemed necessary, as all components appeared to be acceptable. Packing was tightened slightly, but leak persisted.

Corrective time: 4 hr.

Availability of parts: Not applicable.

F9 (405 hr): Piston failure in same cylinder as F8. Broken where piston meets rod (threaded connection).

Cause: Possible misalignment and/or mechanical vibration.

Fix: New piston and rod assembly necessary as well as packing gland assembly. All necessary parts were ordered and were not delivered to sight for 54 working days after a purchase agreement was established (see comment). Pumping unit never fixed because of manufacturer delays.

Corrective time: 6 hr (estimate based on previous maintenance).

Availability of parts: Manufacturer had no parts readily available and had to machine the parts. This resulted in unexpected delays of testing and ultimately the cessation of the Union pumping unit for this test.

Comment: Verbal communications with the manufacturer revealed the pump to be singularly made for BRDEC. Spare parts were not readily available because of this and had to be manufactured to meet replacement requirements. Availability of spare parts, in this instance, is poor.

Summing all the corrective times for the Union pumping unit gives a total of 10 man-hours devoted to corrective maintenance. This yields a corrective maintenance time ratio of

$$MR2 = 8\ hr/405\ hr$$

$$MR2 = 0.020$$

Preventive maintenance time was found to be 6.5 hr (1 hr for every 63 hr of pump operation) making routine checks on all pumping unit components. This establishes a preventive maintenance time ratio of

$$MR3 = 6.5\ hr/405\ hr$$

$$MR3 = 0.016$$

Total maintenance time is the sum of preventive and corrective maintenance, which is 16.5 hr. This yields a total maintenance time ratio of

$$MR1 = 16.5\ hr/405\ hr$$

$$MR1 = 0.041$$

The *MTTR* is established as (10/2) 5.0 hr. Thus, the inherent availability is defined.

$$Ai = \frac{202.5}{(202.5 + 5.0)}$$

$$Ai = 0.976$$

Sundstrand pump with no damper

Figure 11 shows the timetable for the Sundstrand pumping unit, which ran for a total of 2,353 hr with no failure events. This establishes a *MTBF* of 2,353 hr/0 (theoretically undefined; an infinitely large approximation will be made for the *MTBF*).

A total of zero man-hours were devoted to corrective maintenance since there were no corrective measures taken. This yields a corrective maintenance time ratio of

$$MR2 = 0\ hr/2{,}353\ hr$$

$$MR2 = 0.0$$

Preventive maintenance time was found to be 12.5 hr (1 hr for every 189 hr of pump operation) making routine checks on all pumping unit components. This establishes a preventive maintenance time ratio of

$$MR3 = 12.5\ hr/2{,}353\ hr$$

$$MR3 = 0.005$$

Total maintenance time is the sum of preventive and corrective maintenance, which is 12.5 hr. This yields a total maintenance time ratio of

$$MR1 = 12.5\ hr/2{,}335\ hr$$

$$MR1 = 0.005$$

The *MTTR* is established as zero. Thus, the inherent availability is defined as *MTBF/MTBF*:

$$Ai = 1.0\ (by\ definition)$$

Table 8 summarizes the reliability, availability, and maintainability test results.

Table 8
RAM Results

	MTBG	*MR1*	*MR2*	*MR3*	*Ai*
Sundstrand	α	0.005	0.0	0.005	1.0
Wheatley	173.7	0.016	0.029	0.044	0.972
Union	202.5	0.041	0.020	0.016	0.976

6 Summary and Conclusions

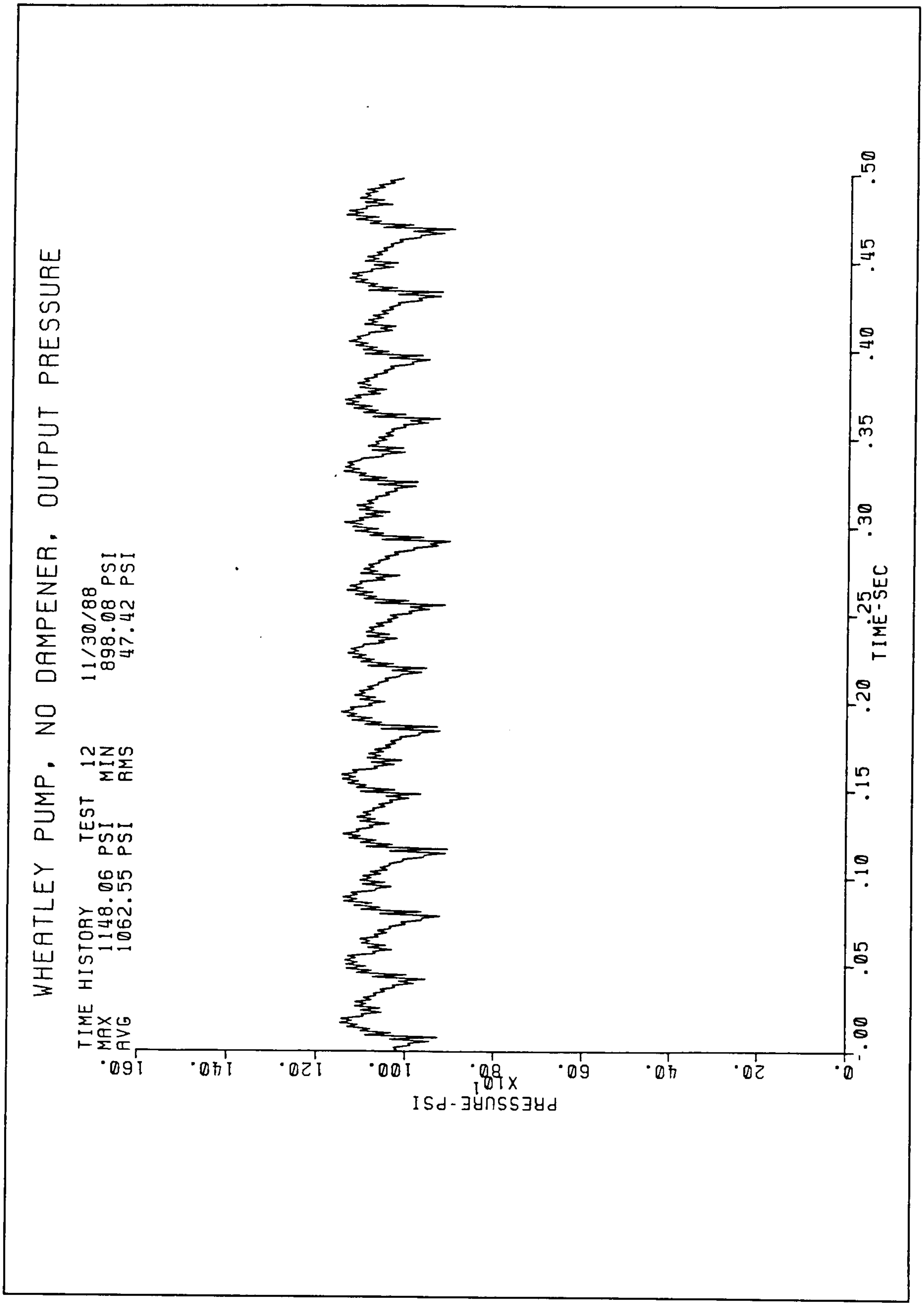
The Sundstrand pump clearly tested superior through all phases of testing. Centrifugal technology is markedly different from positive displacement and has advantages and disadvantages. Most notably, the Sundstrand was half as efficient as the Union and Wheatley pumps, thus requiring twice the power to operate under similar conditions. However, because of its light weight, lack of pulsation damper, superior RAM characteristics, and low vibrations, other technologies such as energy recovery systems and smart motor control devices may lessen the power requirement (generator size) to start and operate centrifugal pumps in conjunction with ROWPU technologies.

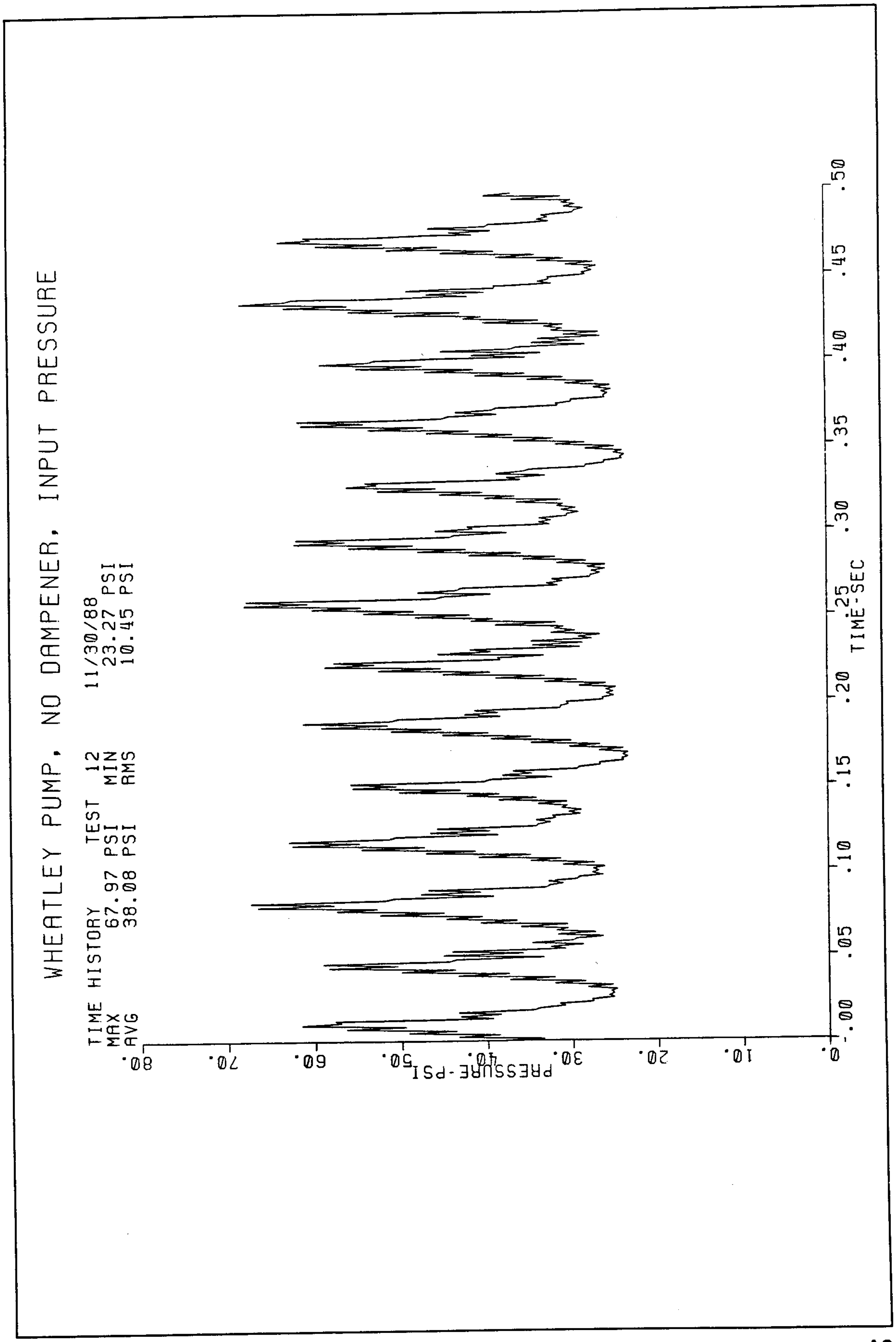
RAM results from the Union and Wheatley pumps required scrutiny because of differing test lengths. RAM ratios shown in Table 8 (and Figure 11) may tend to change with additional test hours. Maintenance ratios would tend to increase with additional operation and MTBF's would tend to decrease.

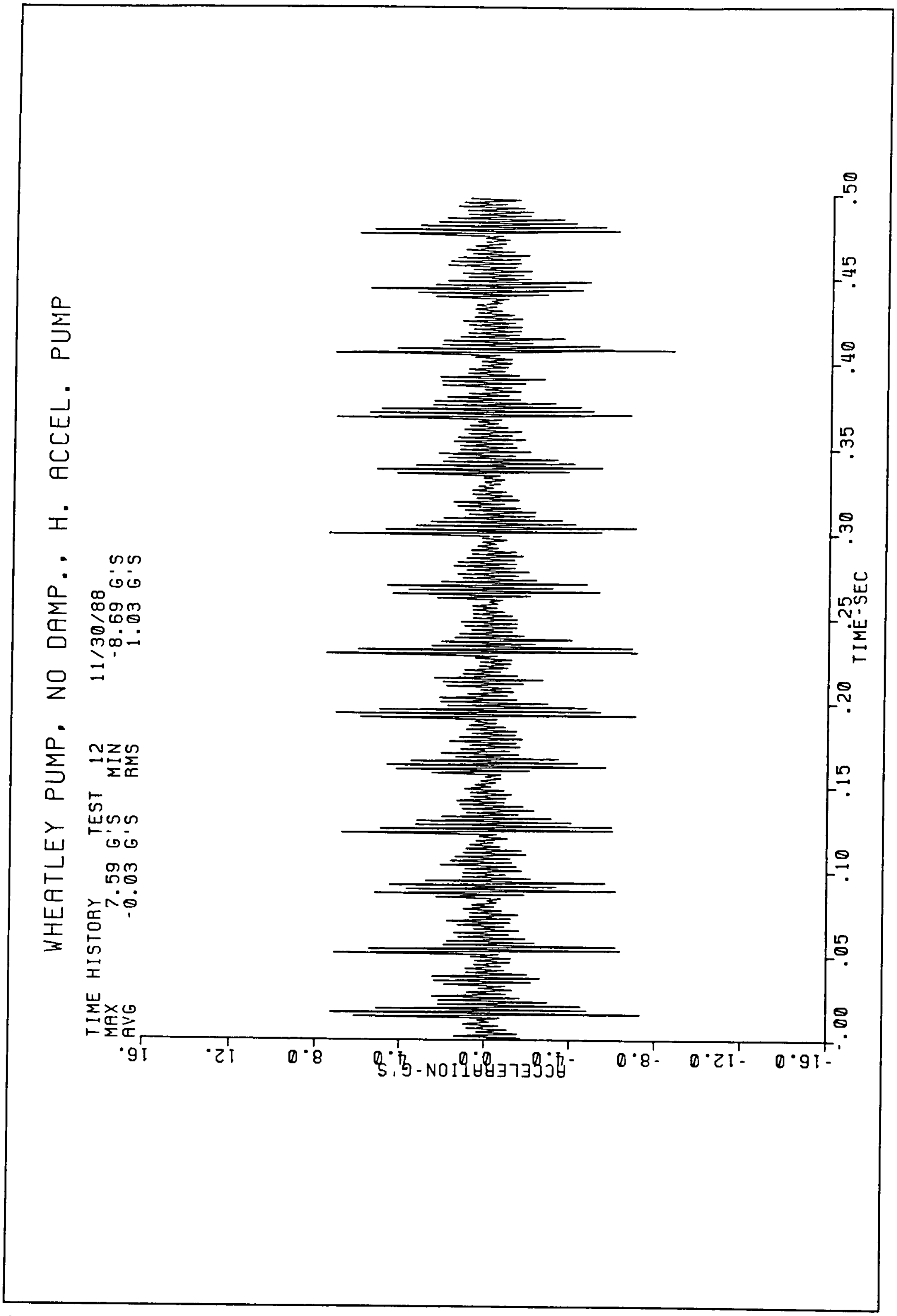
The effects of increased operation hours on inherent availability are unknown.

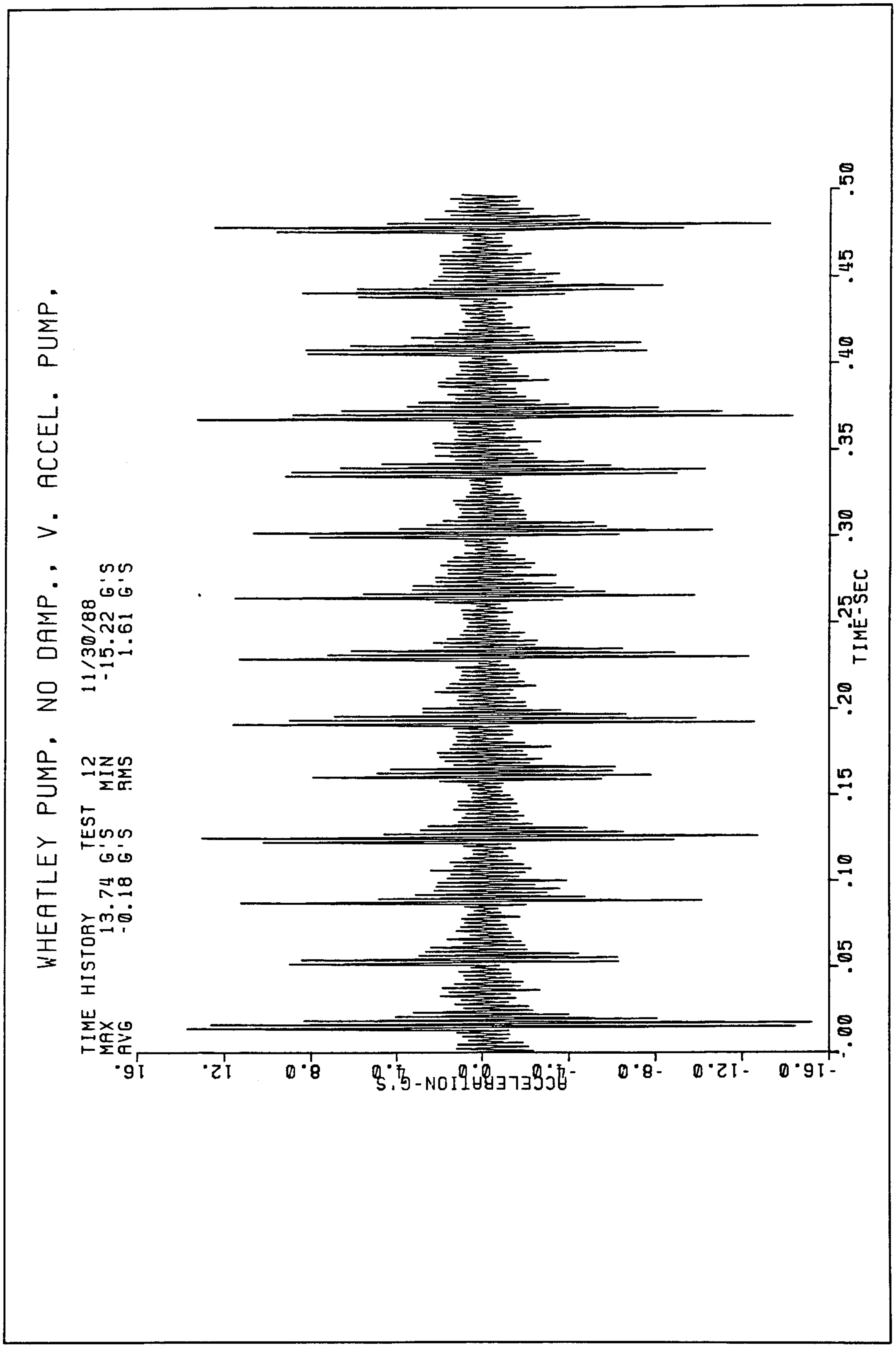
Appendix A
Wheatley Pump

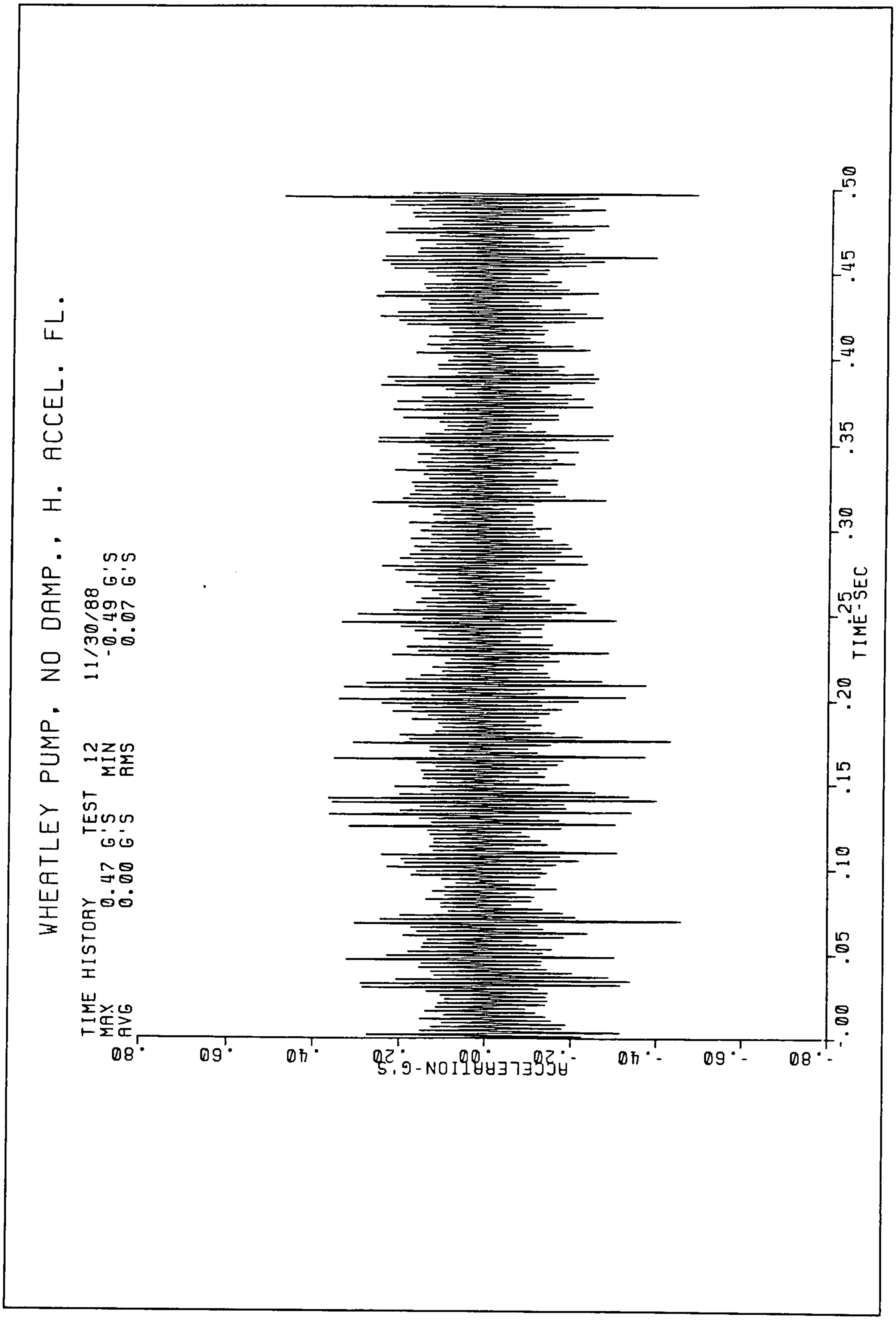
No Pulsation Dampener


WHEATLEY PUMP, NO DAMPENER, OUTPUT PRESSURE
TIME HISTORY TEST 12 11/30/88
MAX 1148.06 PSI MIN 898.08 PSI
AVG 1062.55 PSI RMS 47.42 PSI
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
PRESSURE-PSI
X10¹
0. 20. 40. 60. 80. 100. 120. 140. 160.


WHEATLEY PUMP, NO DAMPENER, INPUT PRESSURE
TIME HISTORY TEST 12 11/30/88
MAX 67.97 PSI MIN 23.27 PSI
AVG 38.08 PSI RMS 10.45 PSI
PRESSURE-PSI
TIME-SEC
0.
10.
20.
30.
40.
50.
60.
70.
80.
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50


WHEATLEY PUMP, NO DAMP., H. ACCEL. PUMP
TIME HISTORY TEST 12 11/30/88
MAX 7.59 G'S MIN -8.69 G'S
AVG -0.03 G'S RMS 1.03 G'S
16.
12.
8.0
4.0
0.0
-4.0
-8.0
-12.0
-16.0
ACCELERATION-G'S
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
TIME-SEC


WHEATLEY PUMP, NO DAMP., V. ACCEL. PUMP,
TIME HISTORY TEST 12 11/30/88
MAX 13.74 G'S MIN -15.22 G'S
AVG -0.18 G'S RMS 1.61 G'S
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
ACCELERATION-G'S
16. 12. 8.0 4.0 0.0 -4.0 -8.0 -12.0 -16.0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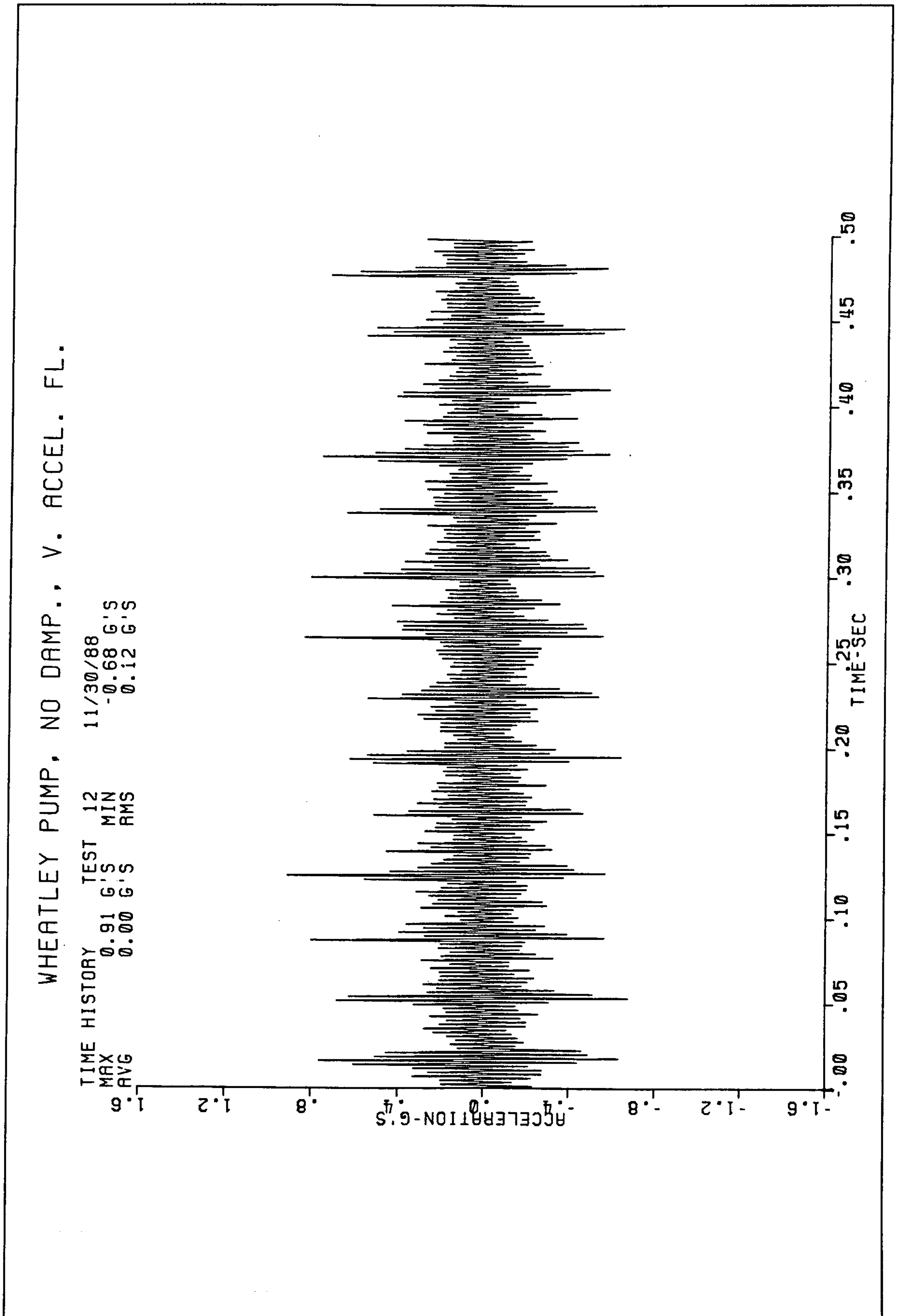
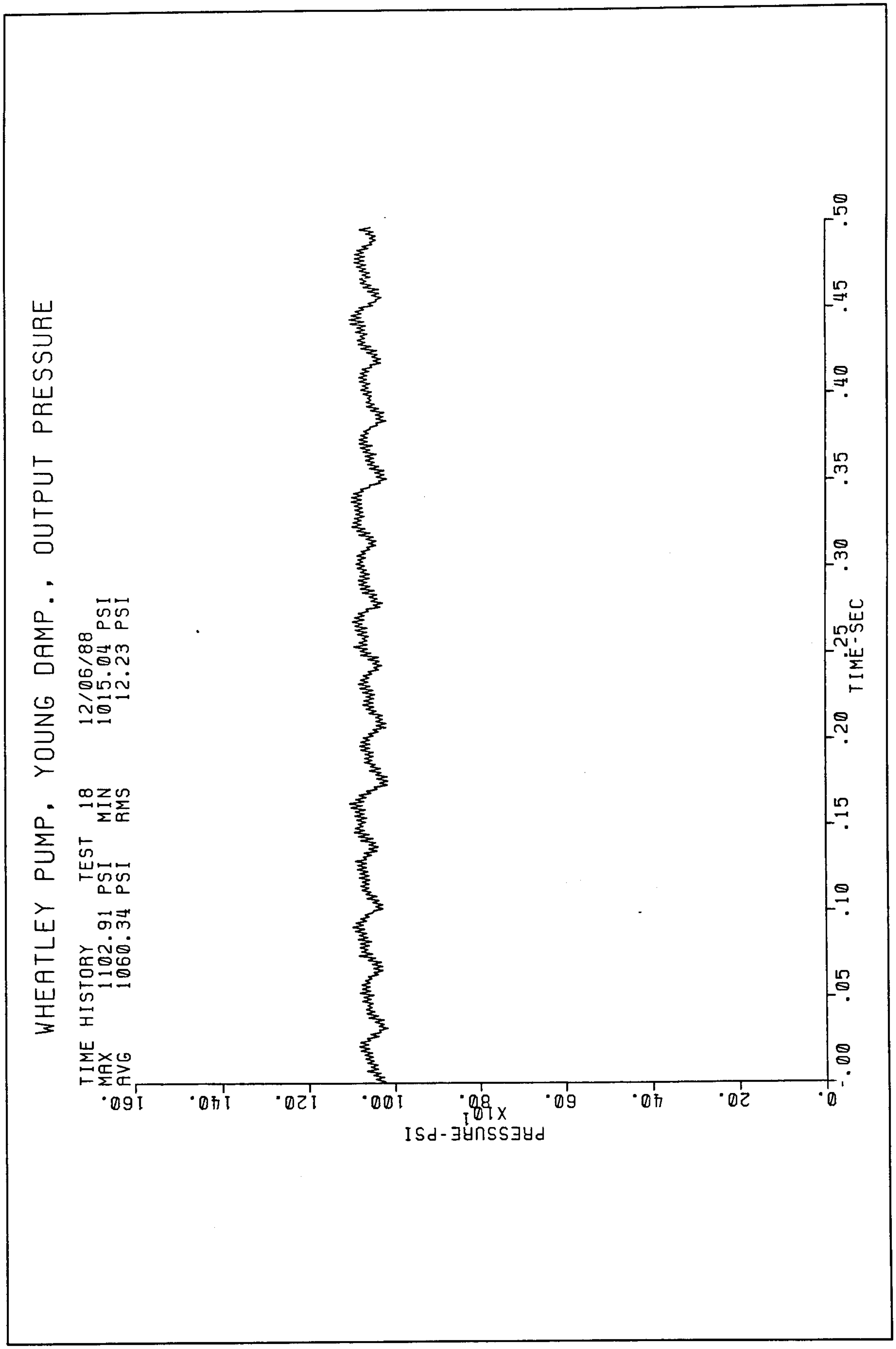
TIME HISTORY TEST 12 11/30/88
MAX 0.47 G'S MIN -0.49 G'S
AVG 0.00 G'S RMS 0.07 G'S
TIME-SEC
ACCELERATION-G'S
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.80
.60
.40
.20
.00
-.20
-.40
-.60
-.80



WHEATLEY PUMP, NO DAMP., V. ACCEL. FL.
TIME HISTORY TEST 12 11/30/88
MAX 0.91 G'S MIN -0.68 G'S
AVG 0.00 G'S RMS 0.12 G'S
ACCELERATION-G'S
1.6
1.2
.8
.4
0
-.4
-.8
-1.2
-1.6
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50

Young Pulsation Dampener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TIME HISTORY TEST 18 12/06/88
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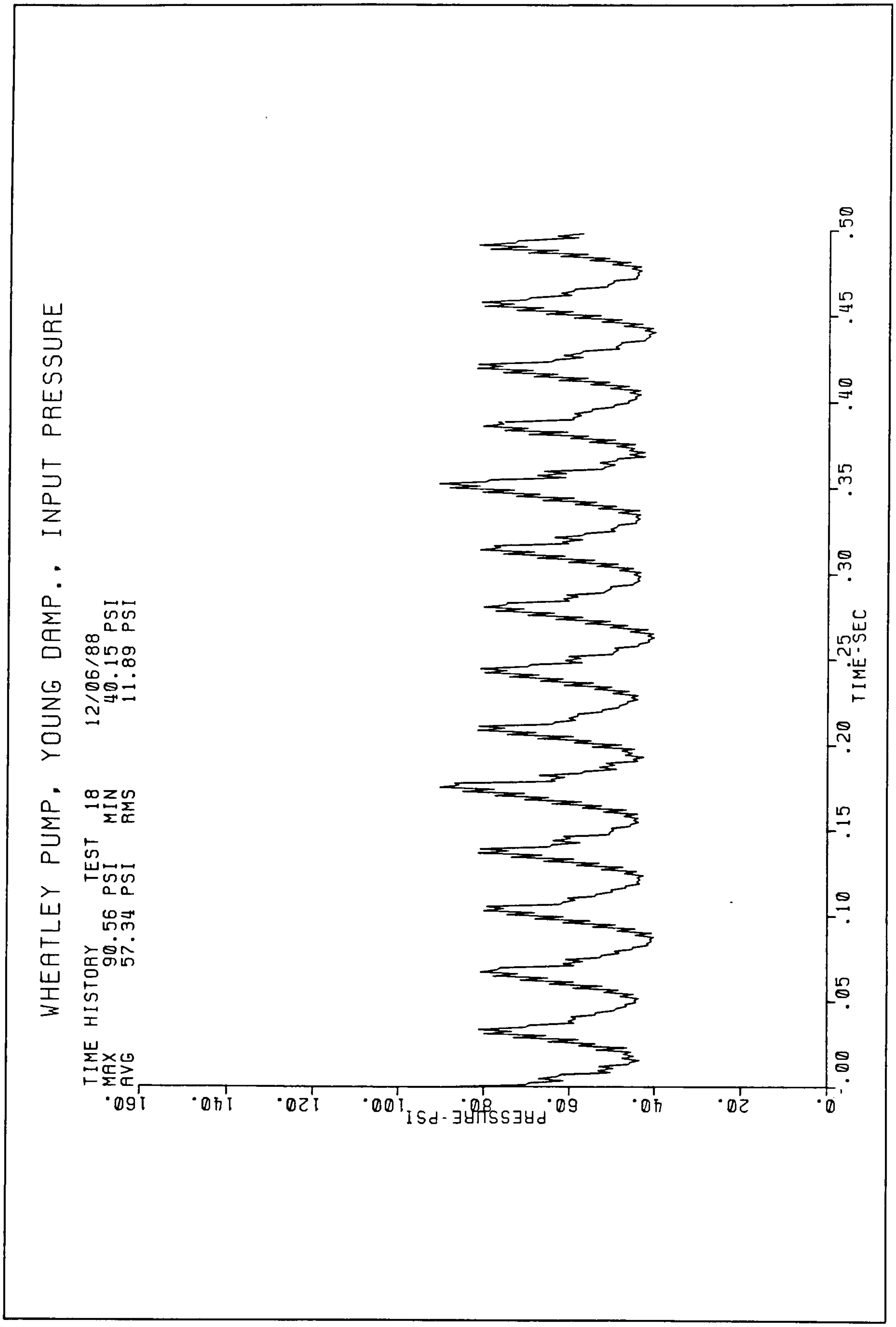
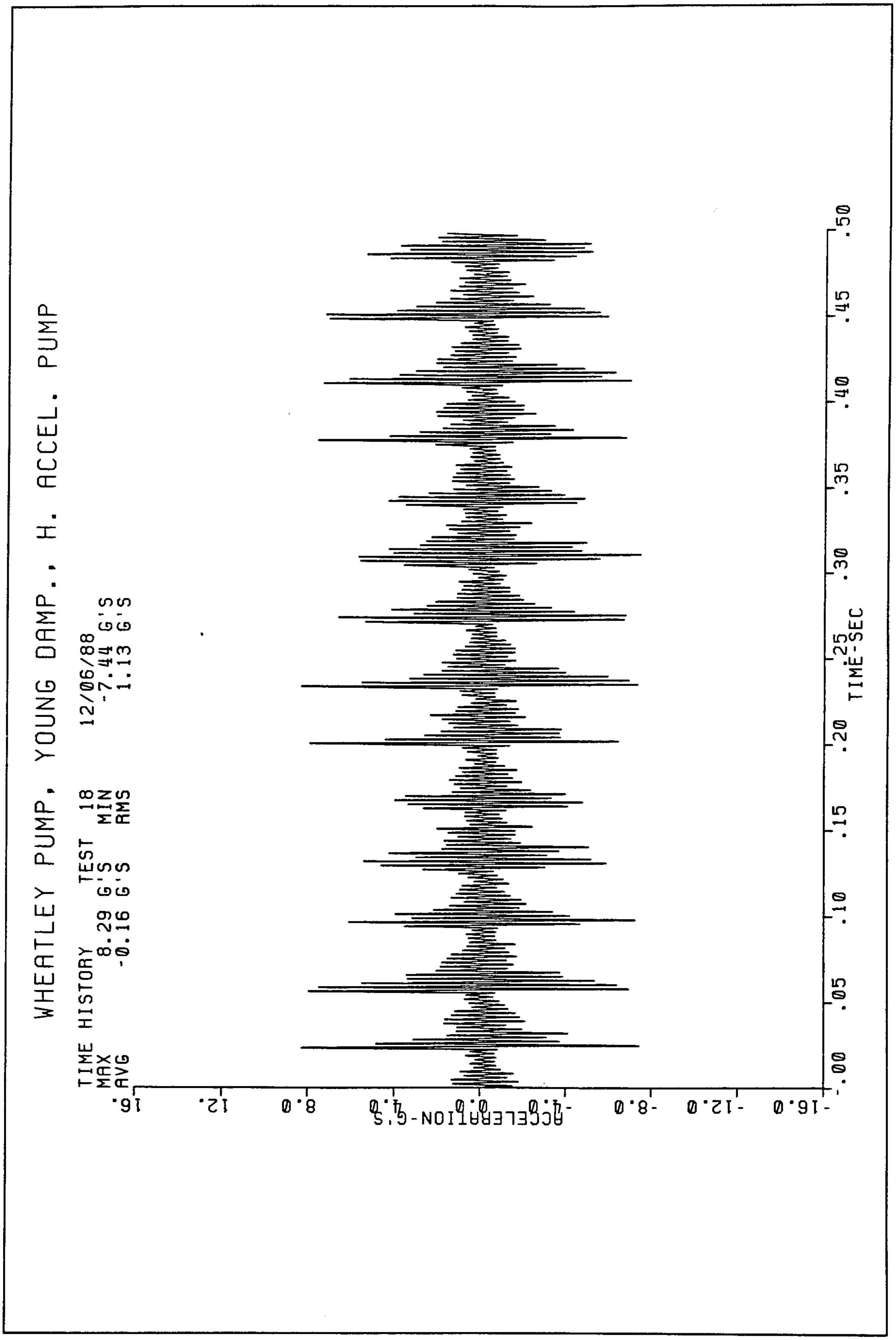
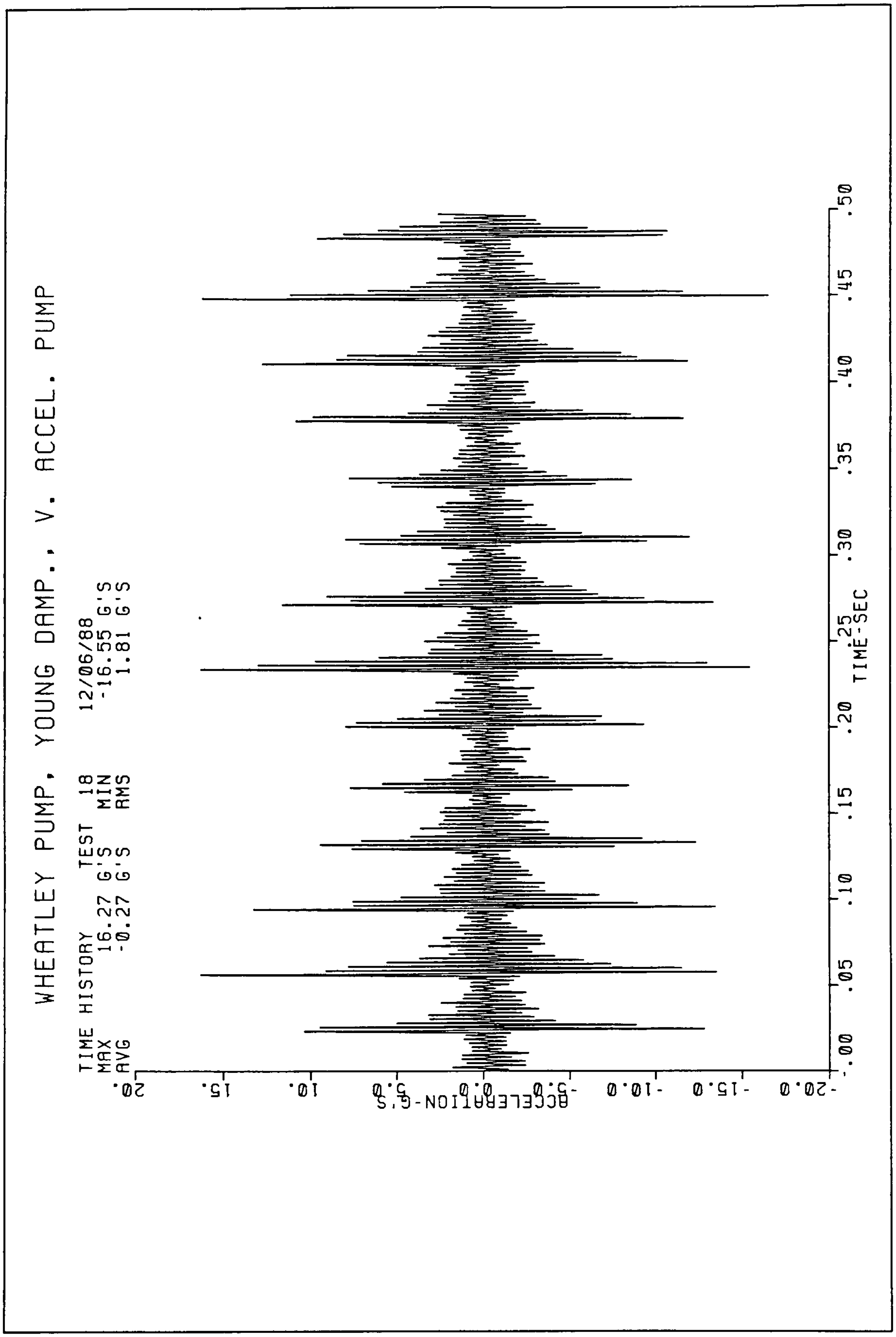
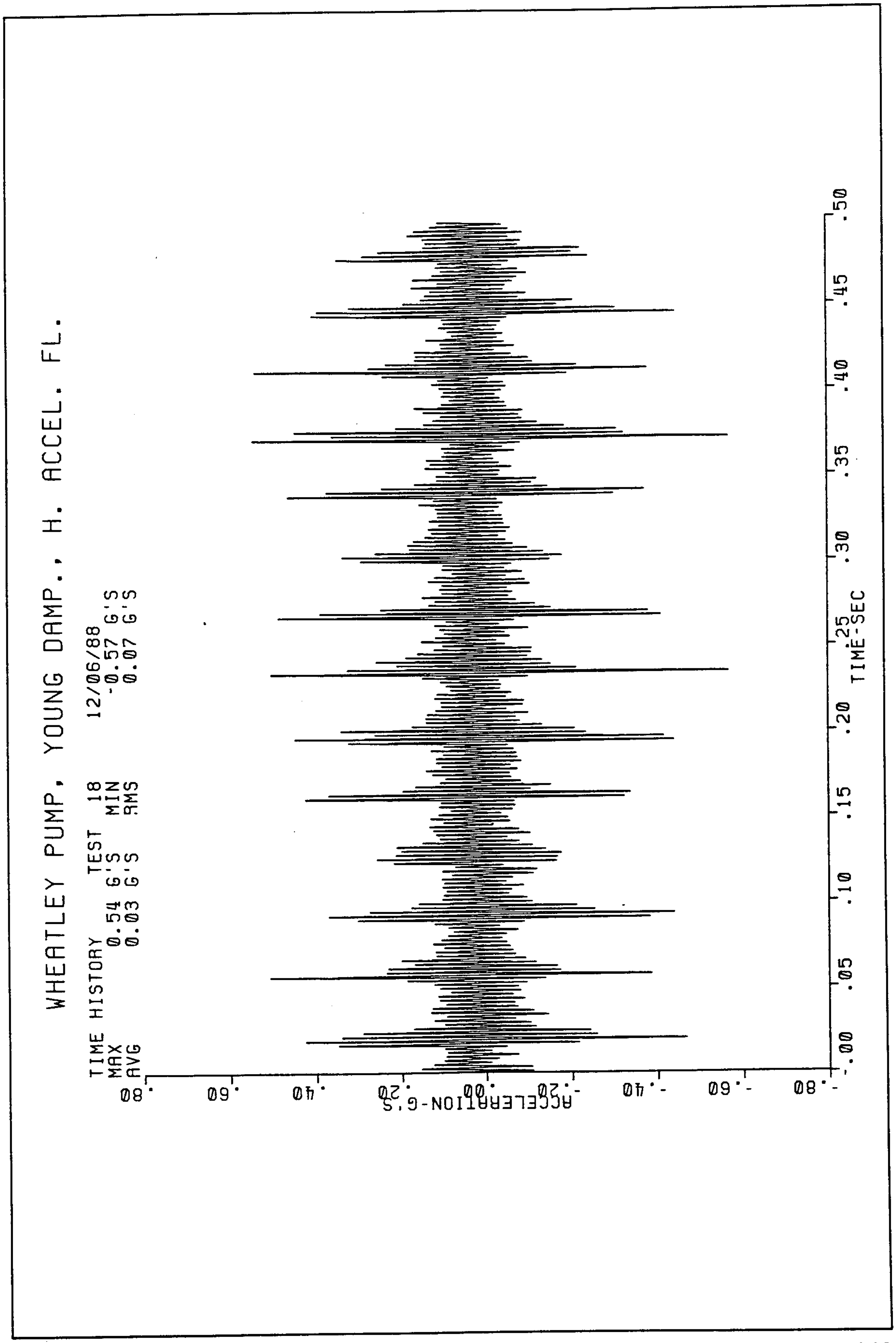
AVG 1060.34 PSI RMS 12.23 PSI
TIME-SEC
PRESSURE-PSI
X10^1

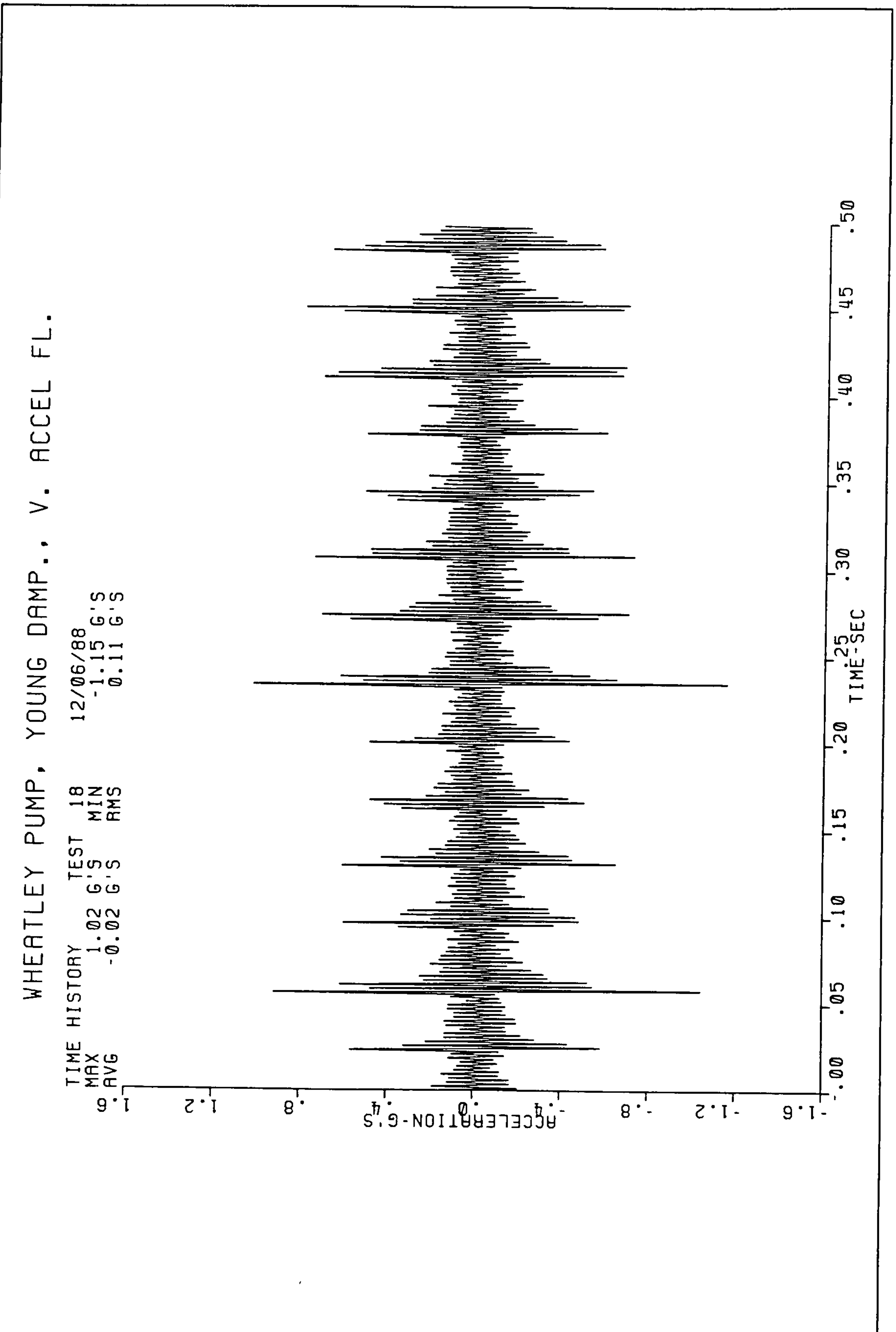

WHEATLEY PUMP, YOUNG DAMP., INPUT PRESSURE
TIME HISTORY TEST 18 12/06/88
MAX 90.56 PSI MIN 40.15 PSI
AVG 57.34 PSI RMS 11.89 PSI
PRESSURE-PSI
0. 20. 40. 60. 80. 100. 120. 140. 160.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


WHEATLEY PUMP, YOUNG DAMP., H. ACCEL. PUMP
TIME HISTORY TEST 18 12/06/88
MAX 8.29 G'S MIN -7.44 G'S
AVG -0.16 G'S RMS 1.13 G'S
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
ACCELERATION-G'S
16.
12.
8.0
4.0
0.0
-4.0
-8.0
-12.0
-16.0

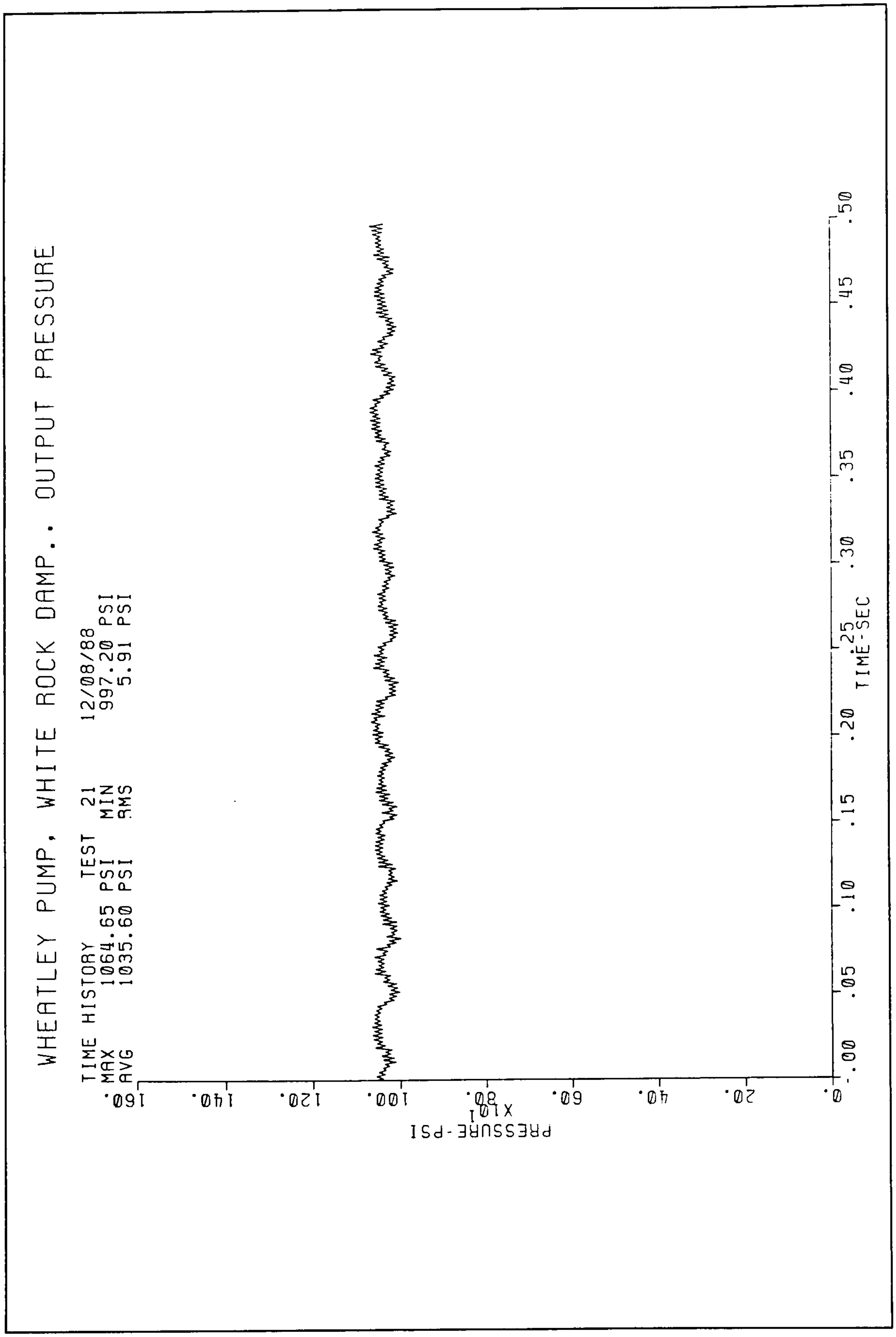

WHEATLEY PUMP, YOUNG DAMP., V. ACCEL. PUMP
TIME HISTORY TEST 18 12/06/88
MAX 16.27 G'S MIN -16.55 G'S
AVG -0.27 G'S RMS 1.81 G'S
TIME-SEC
ACCELERATION-G'S

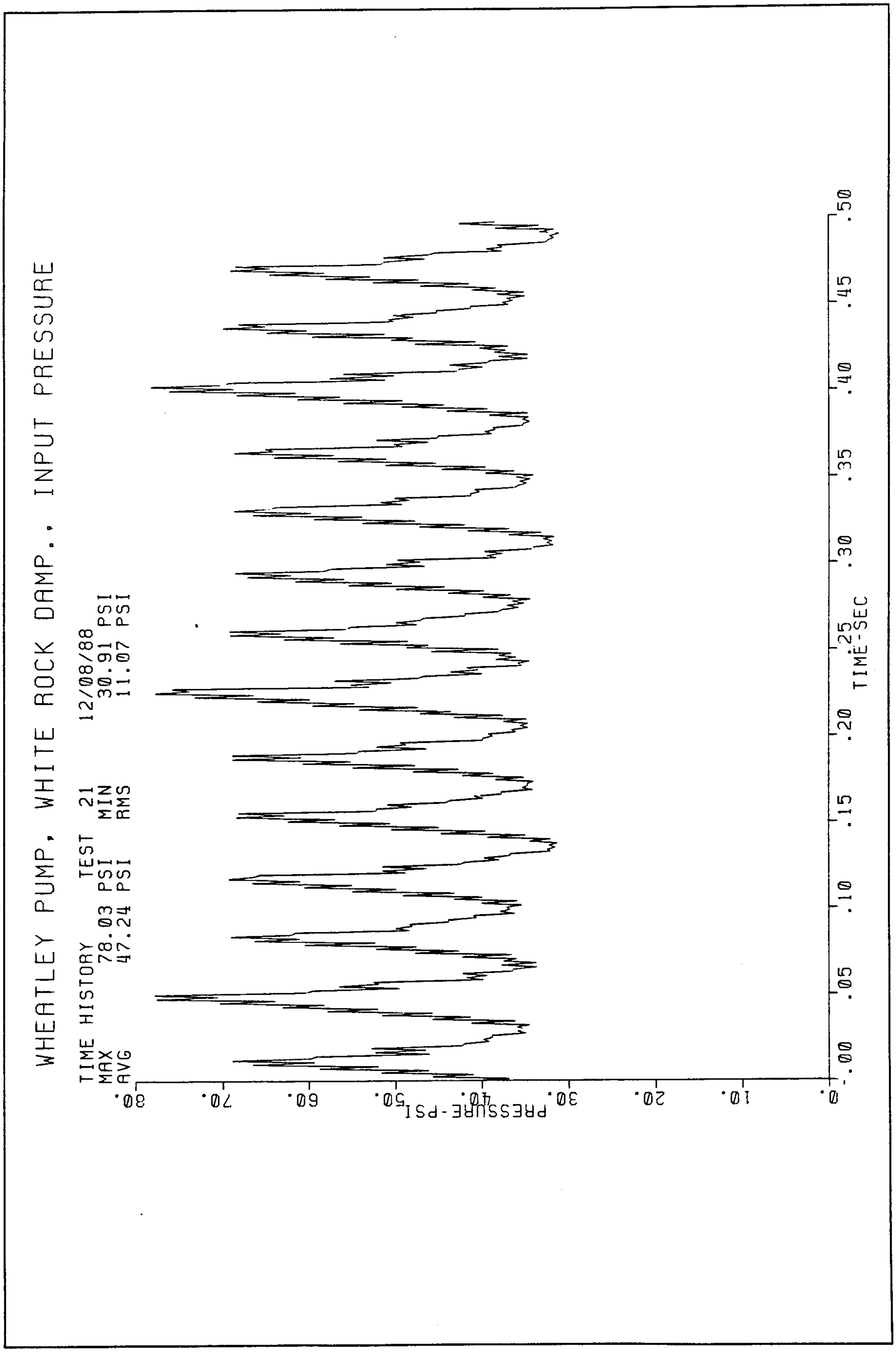


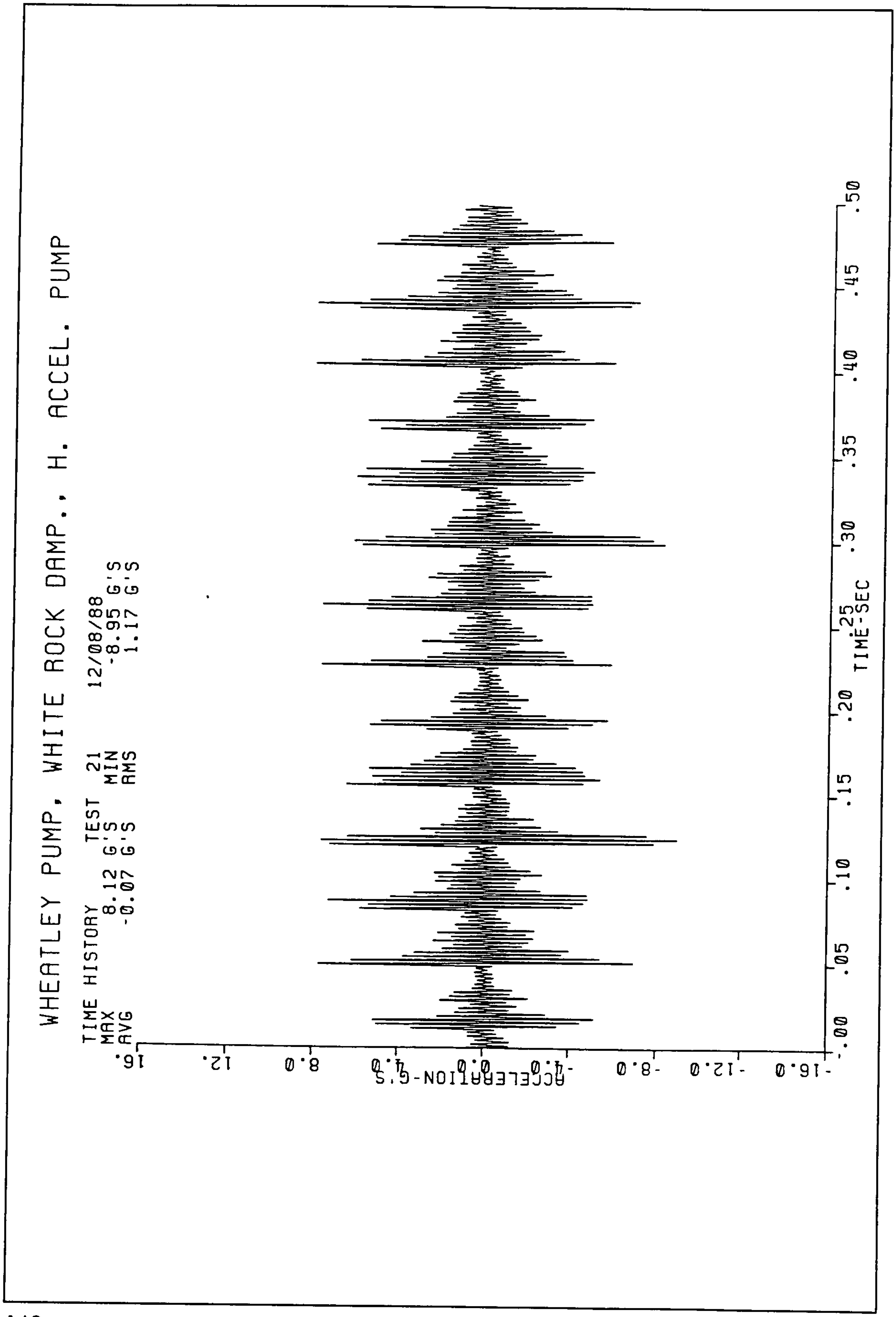
WHEATLEY PUMP, YOUNG DAMP., H. ACCEL. FL.
TIME HISTORY TEST 18 12/06/88
MAX 0.54 G'S MIN -0.57 G'S
AVG 0.03 G'S RMS 0.07 G'S
ACCELERATION-G'S
.80
.60
.40
.20
.00
-.20
-.40
-.60
-.80
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50

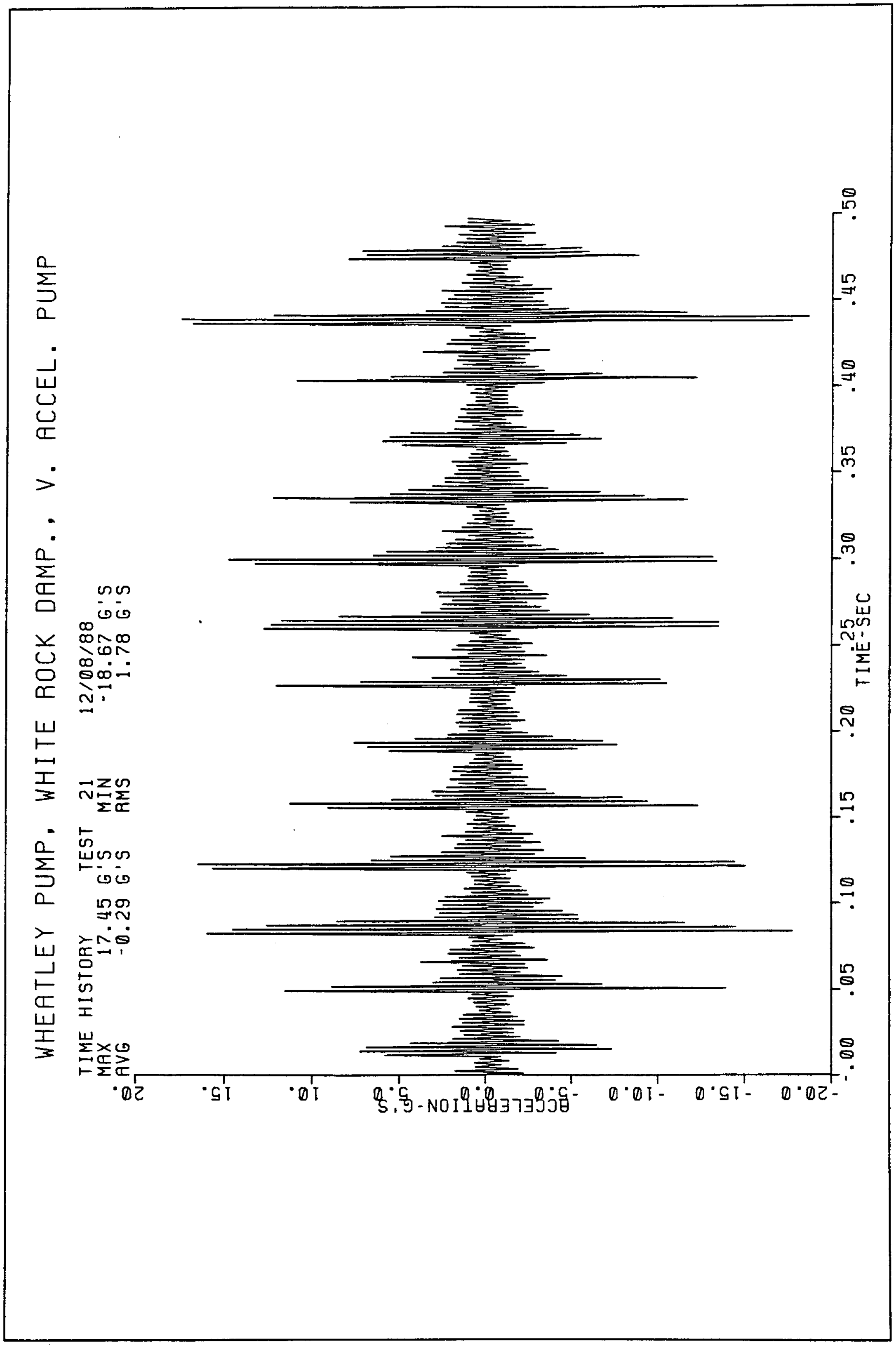

WHEATLEY PUMP, YOUNG DAMP., V. ACCEL FL.
TIME HISTORY TEST 18 12/06/88
MAX 1.02 G'S MIN -1.15 G'S
AVG -0.02 G'S RMS 0.11 G'S
TIME-SEC
ACCELERATION-G'S

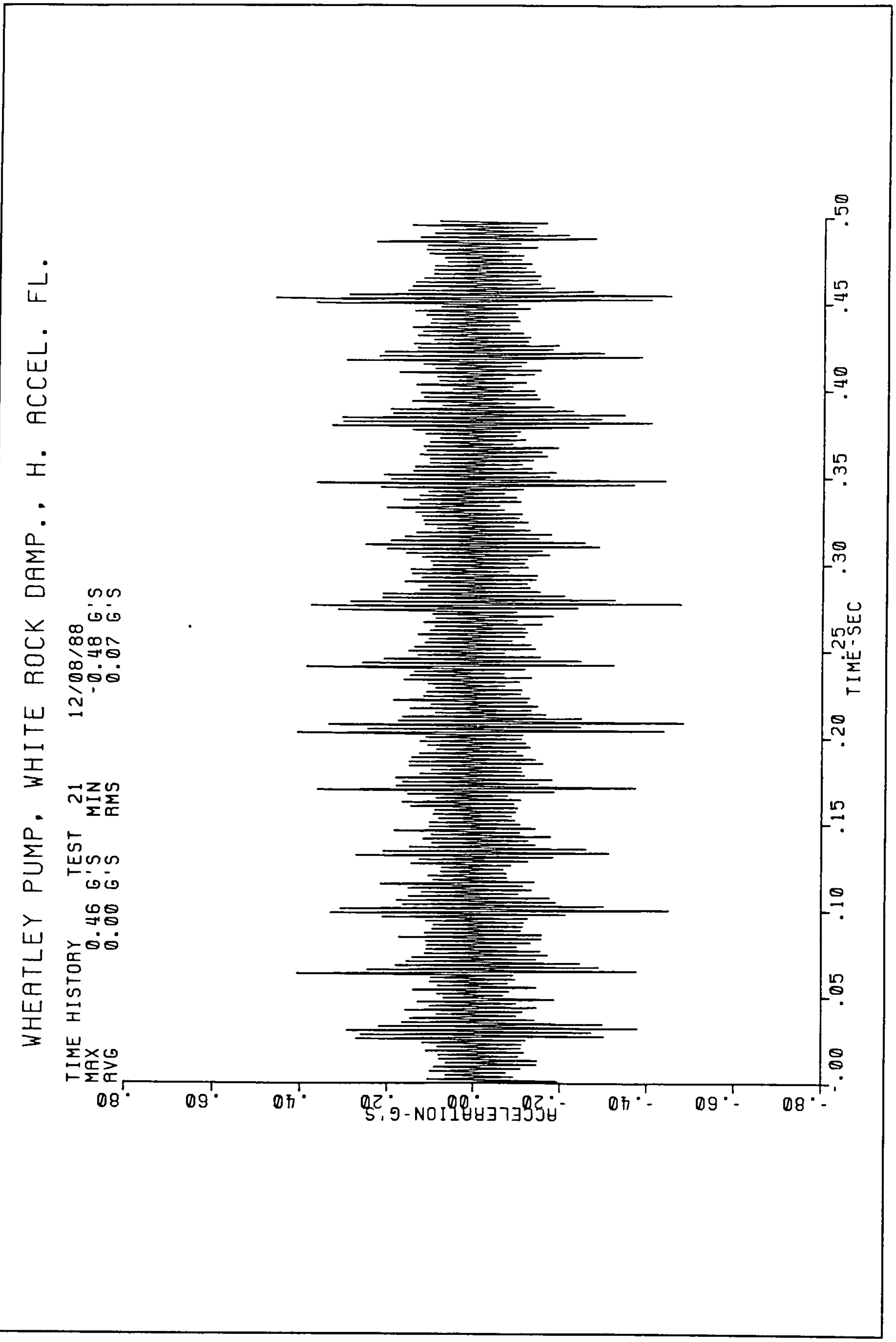
White Rock Pulsation Dampener


WHEATLEY PUMP, WHITE ROCK DAMP.. OUTPUT PRESSURE
TIME HISTORY TEST 21 12/08/88
MAX 1064.65 PSI MIN 997.20 PSI
AVG 1035.60 PSI RMS 5.91 PSI
PRESSURE-PSI
X10¹
0
20.
40.
60.
80.
100.
120.
140.
160.
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50

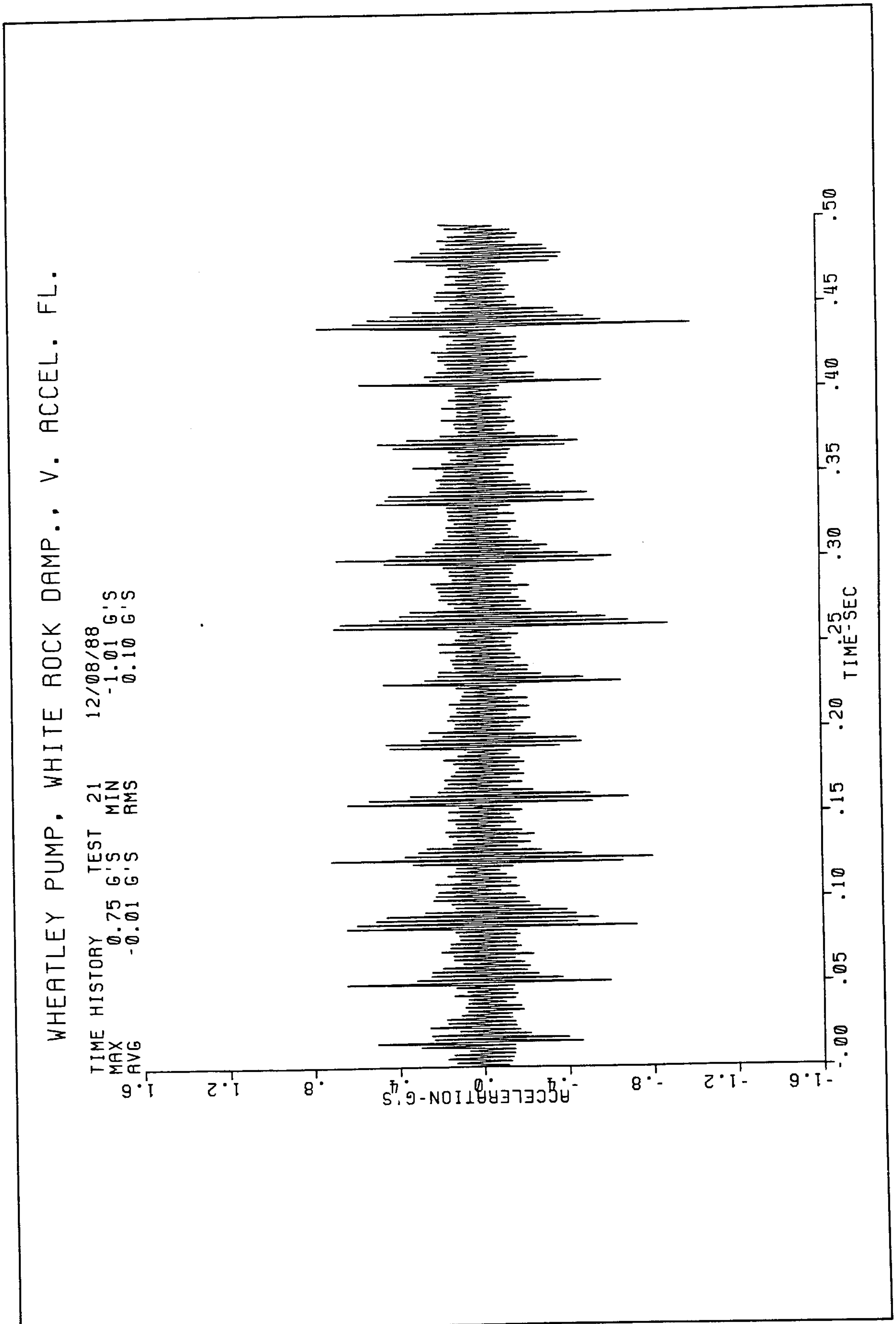

WHEATLEY PUMP, WHITE ROCK DAMP.. INPUT PRESSURE
TIME HISTORY TEST 21 12/08/88
MAX 78.03 PSI MIN 30.91 PSI
AVG 47.24 PSI RMS 11.07 PSI
TIME-SEC
PRESSURE-PSI
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
0. 10. 20. 30. 40. 50. 60. 70. 80.


WHEATLEY PUMP, WHITE ROCK DAMP., H. ACCEL. PUMP
TIME HISTORY TEST 21 12/08/88
MAX 8.12 G'S MIN -8.95 G'S
AVG -0.07 G'S RMS 1.17 G'S
TIME-SEC
ACCELERATION-G'S


WHEATLEY PUMP, WHITE ROCK DAMP., V. ACCEL. PUMP
TIME HISTORY TEST 21 12/08/88
MAX 17.45 G'S MIN -18.67 G'S
AVG -0.29 G'S RMS 1.78 G'S
TIME-SEC
ACCELERATION-G'S

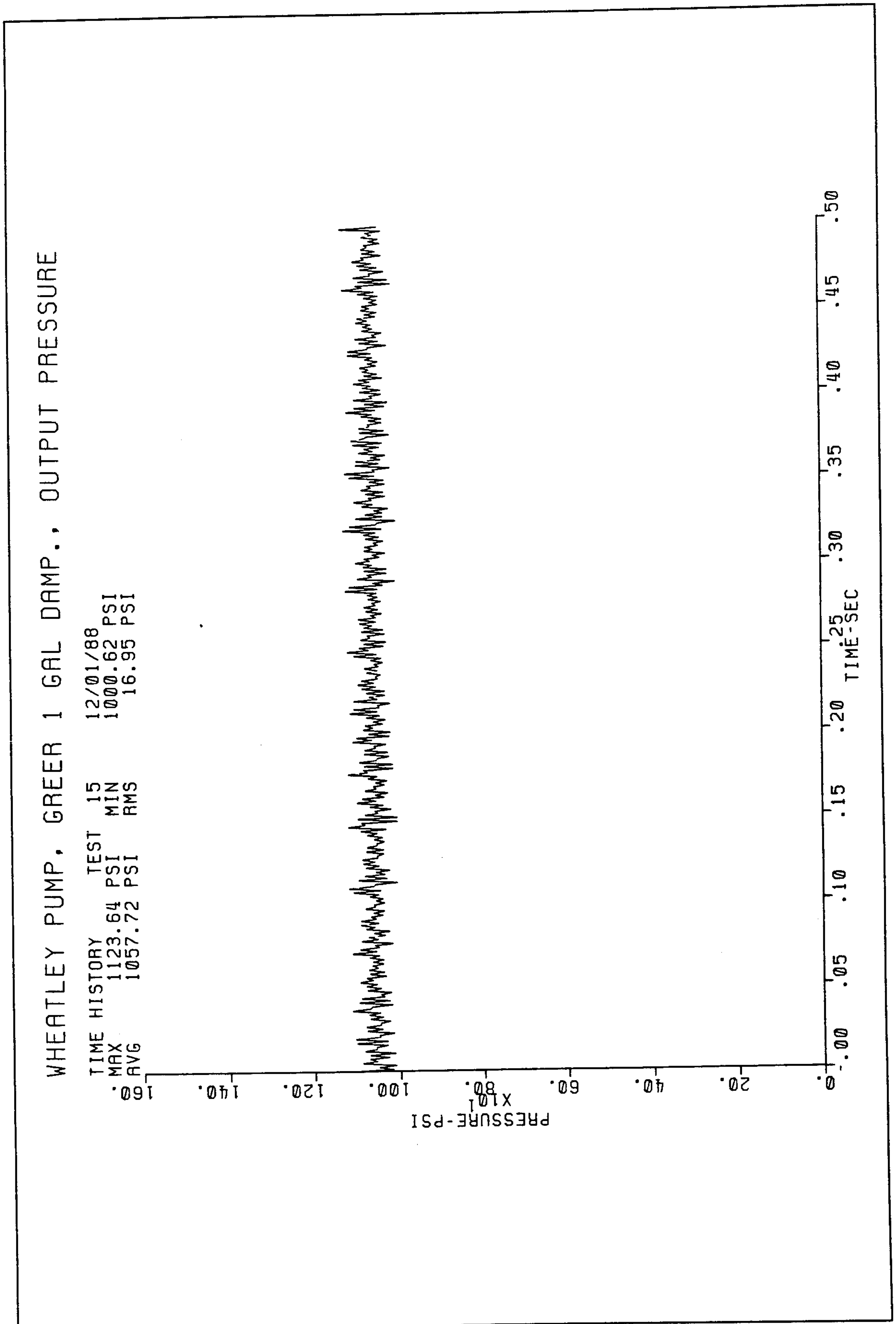


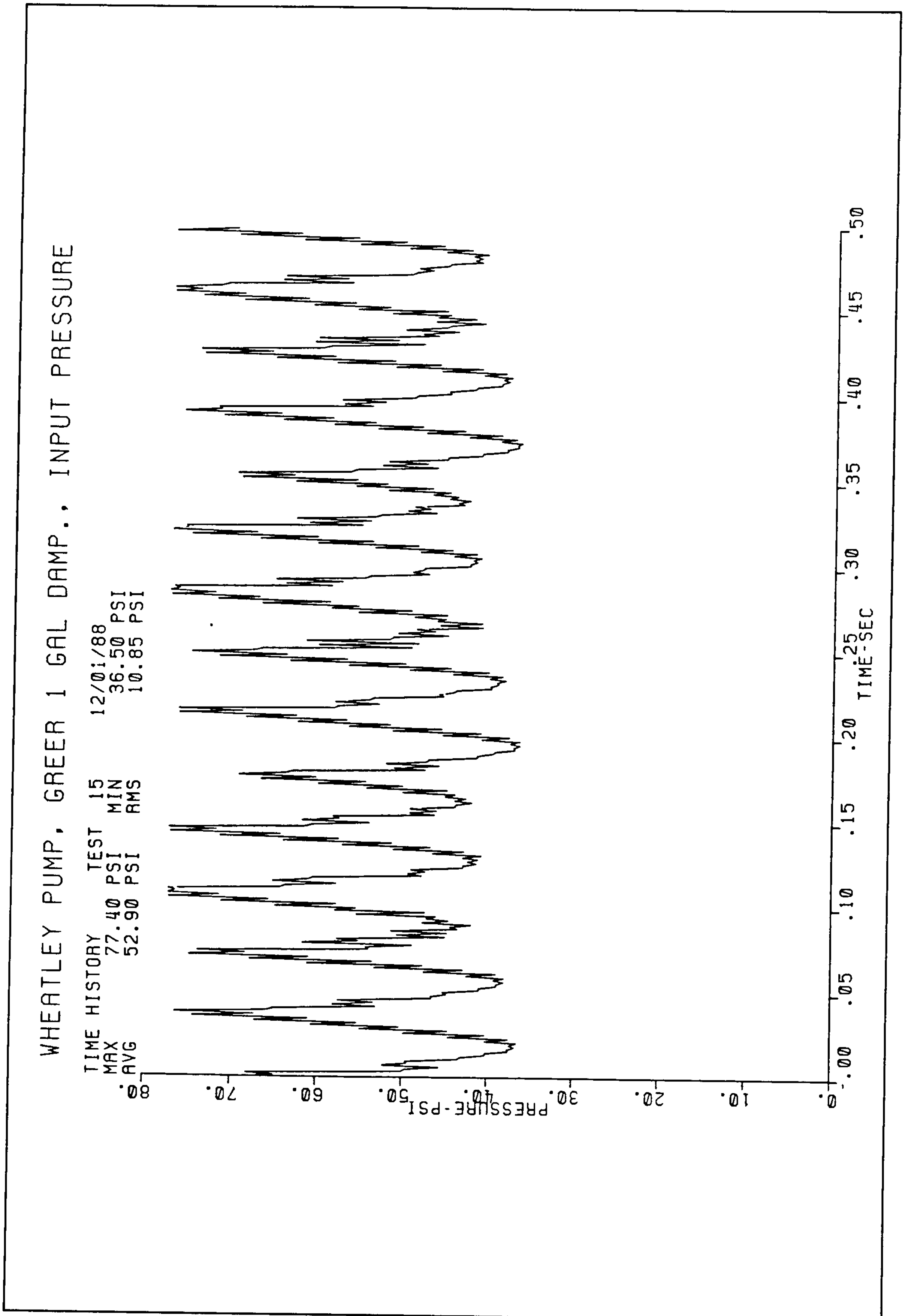
WHEATLEY PUMP, WHITE ROCK DAMP., H. ACCEL. FL.
TIME HISTORY TEST 21 12/08/88
MAX 0.46 G'S MIN -0.48 G'S
AVG 0.00 G'S RMS 0.07 G'S
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
TIME-SEC
.80
.60
.40
.20
.00
-.20
-.40
-.60
-.80
ACCELERATION-G'S

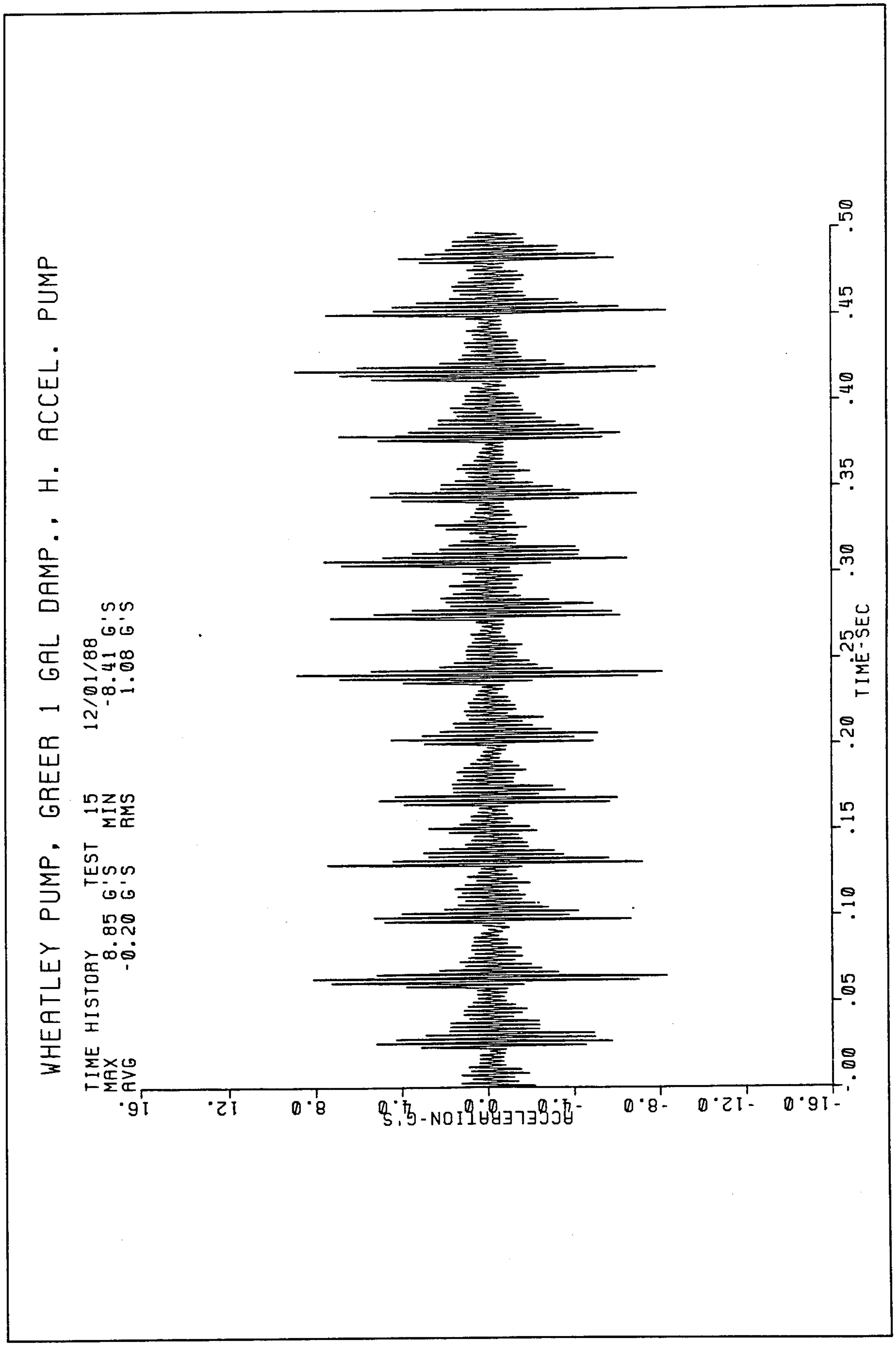

WHEATLEY PUMP, WHITE ROCK DAMP., V. ACCEL. FL.
TIME HISTORY TEST 21 12/08/88
MAX 0.75 G'S MIN -1.01 G'S
AVG -0.01 G'S RMS 0.10 G'S
ACCELERATION-G'S
1.6 1.2 .8 .4 .0 -.4 -.8 -1.2 -1.6
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

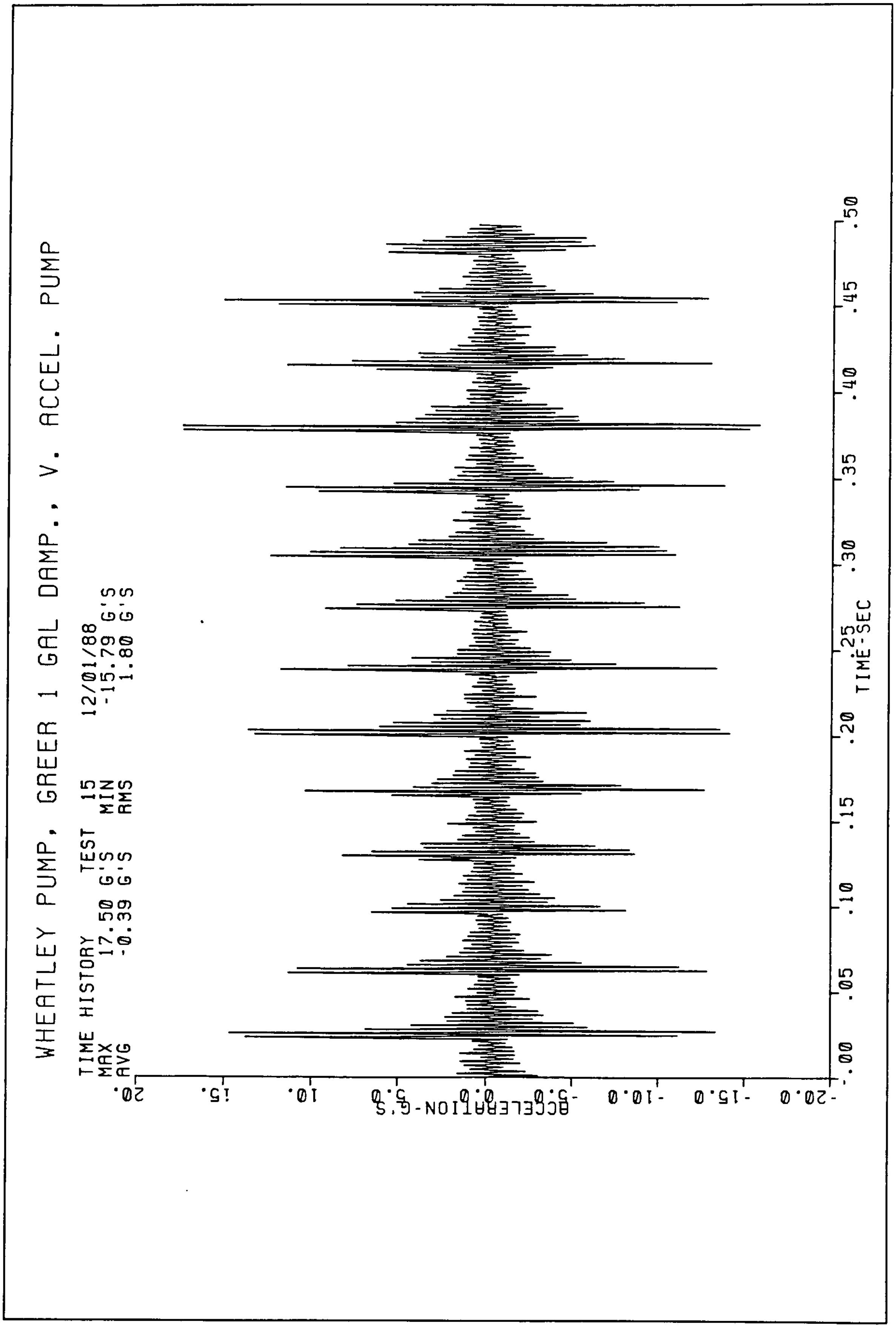
A21

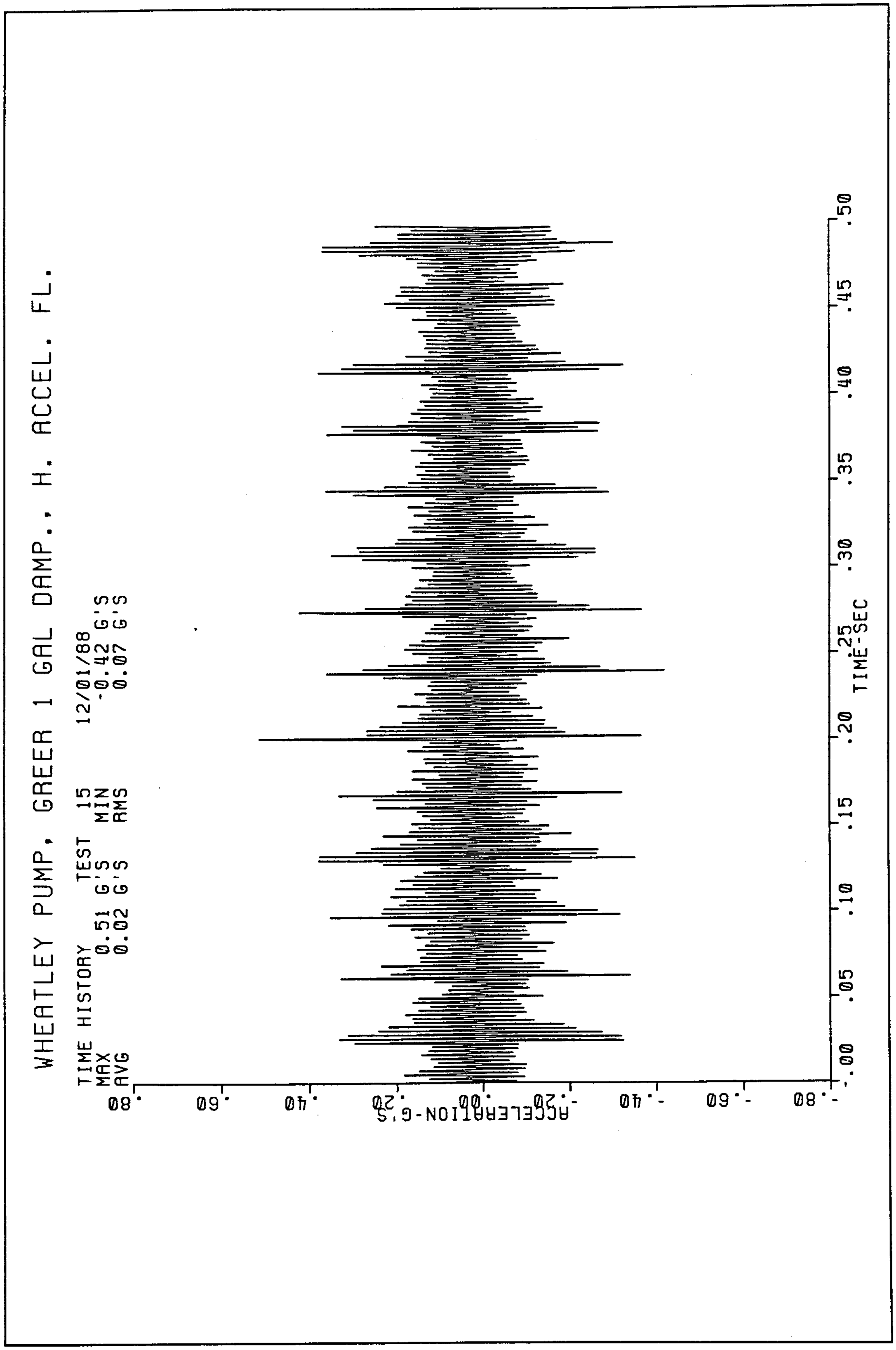
Greer 1-Gal (4-Qt) Pulsation Dampener

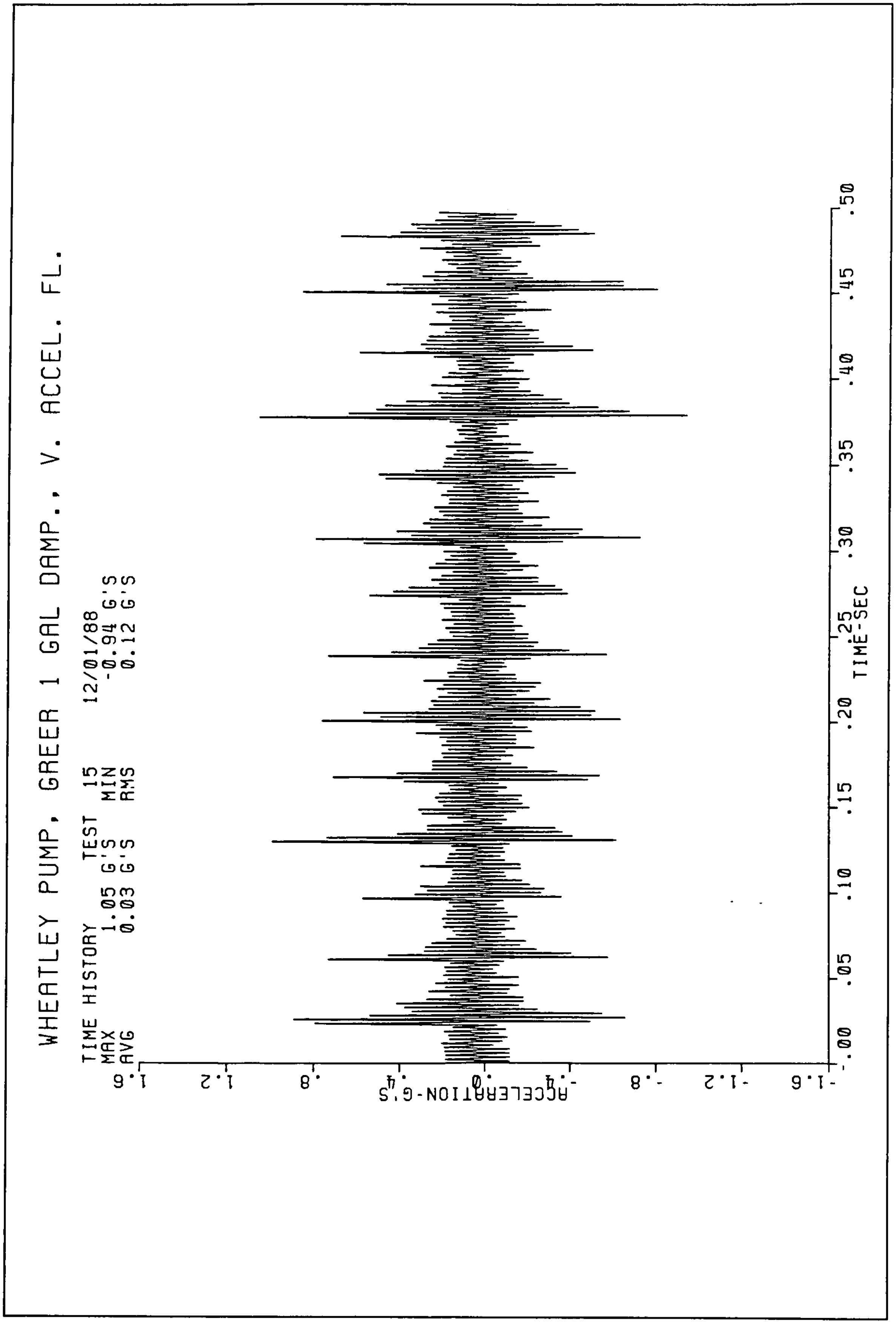

WHEATLEY PUMP, GREER 1 GAL DAMP., OUTPUT PRESSURE
TIME HISTORY TEST 15 12/01/88
MAX 1123.64 PSI MIN 1000.62 PSI
AVG 1057.72 PSI RMS 16.95 PSI
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
PRESSURE-PSI
X10¹
0.
20.
40.
60.
80.
100.
120.
140.
160.


WHEATLEY PUMP, GREER 1 GAL DAMP., INPUT PRESSURE
TIME HISTORY TEST 15 12/01/88
MAX 77.40 PSI MIN 36.50 PSI
AVG 52.90 PSI RMS 10.85 PSI
PRESSURE-PSI
TIME-SEC


WHEATLEY PUMP, GREER 1 GAL DAMP., H. ACCEL. PUMP
TIME HISTORY TEST 15 12/01/88
MAX 8.85 G'S MIN -8.41 G'S
AVG -0.20 G'S RMS 1.08 G'S
TIME-SEC
ACCELERATION-G'S
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
16. 12. 8.0 4.0 0.0 -4.0 -8.0 -12.0 -16.0

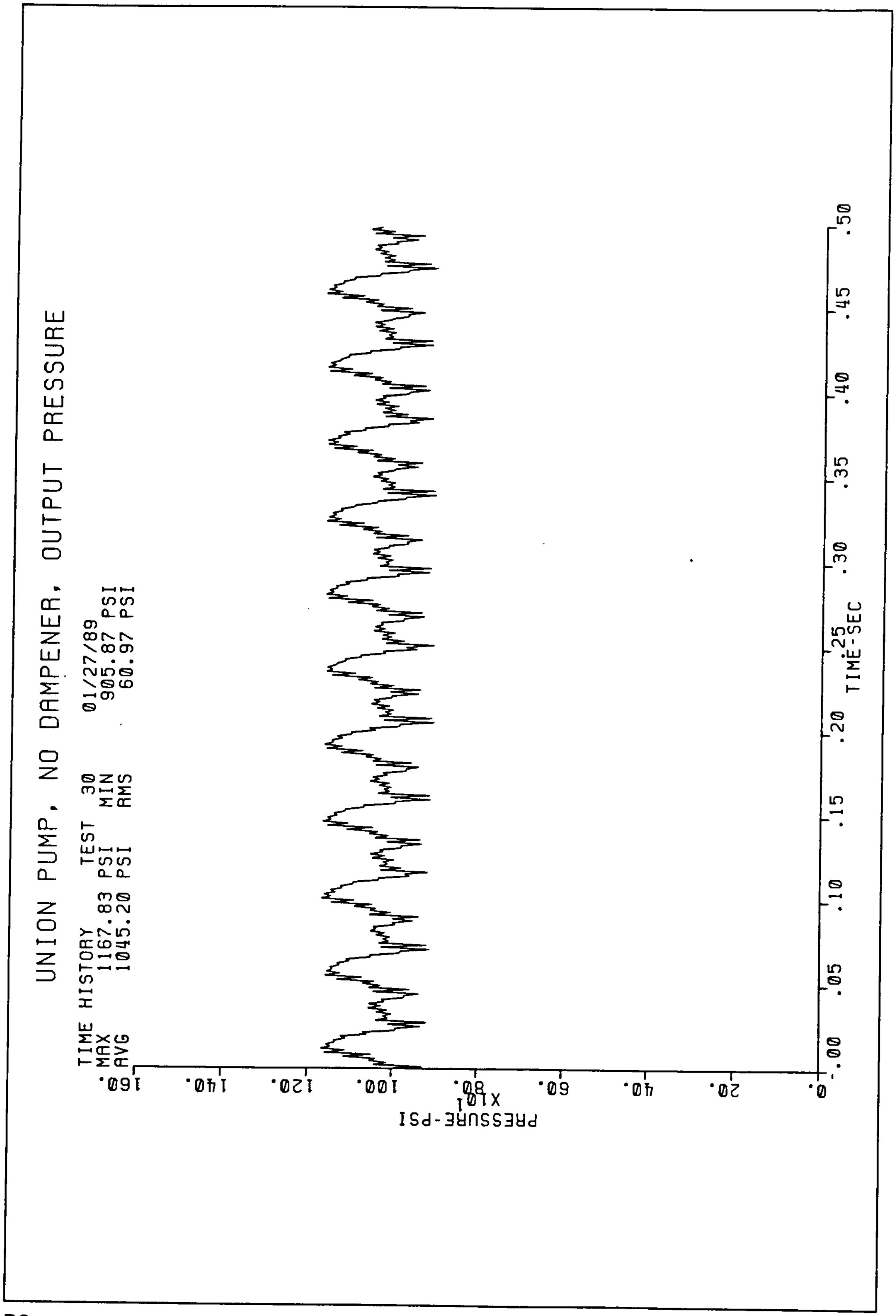

WHEATLEY PUMP, GREER 1 GAL DAMP., V. ACCEL. PUMP
TIME HISTORY TEST 15 12/01/88
MAX 17.50 G'S MIN -15.79 G'S
AVG -0.39 G'S RMS 1.80 G'S
ACCELERATION-G'S
20. 15. 10. 5.0 0.0 -5.0 -10.0 -15.0 -20.0
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

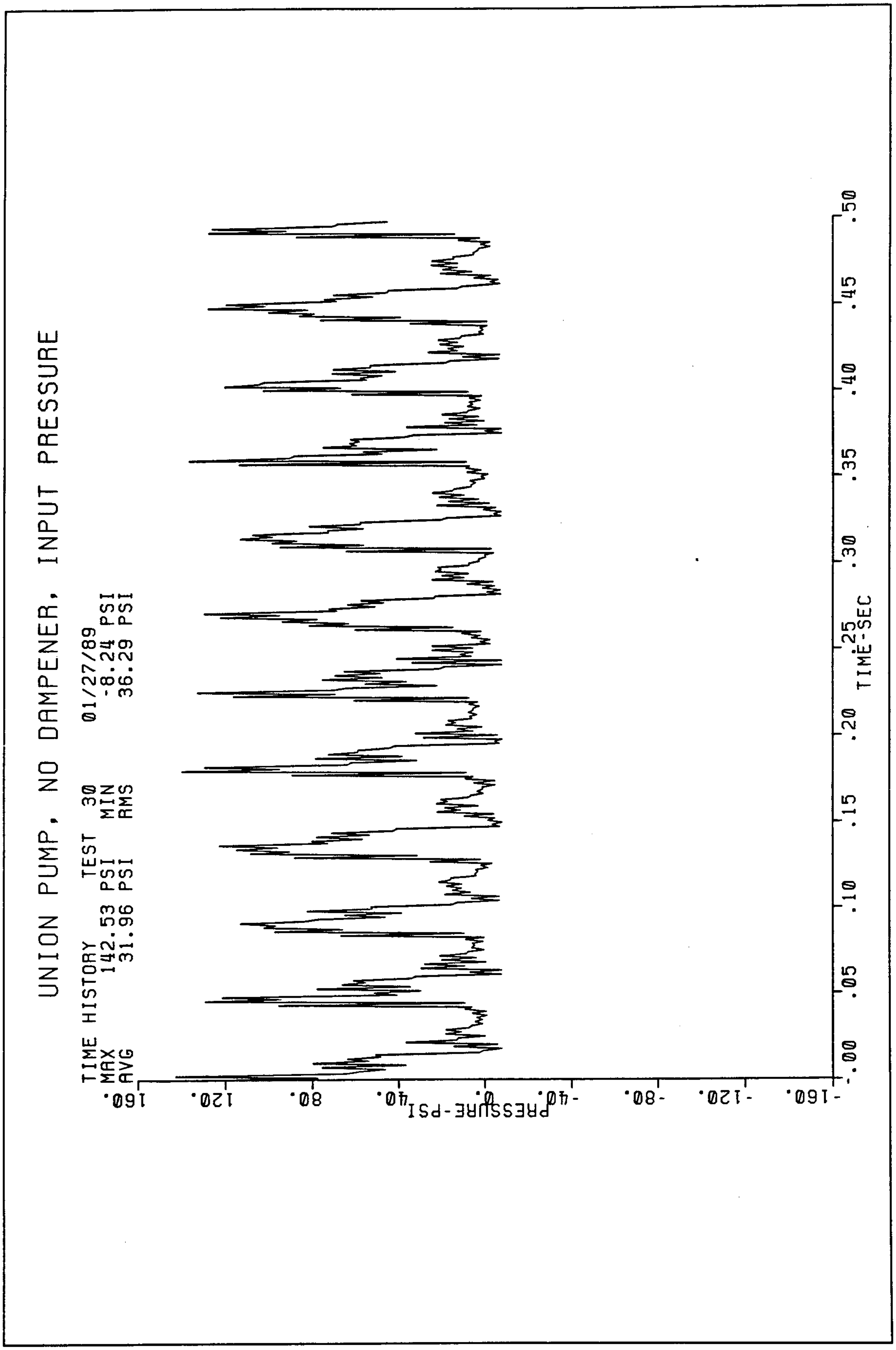

WHEATLEY PUMP, GREER 1 GAL DAMP., H. ACCEL. FL.
TIME HISTORY TEST 15 12/01/88
MAX 0.51 G'S MIN -0.42 G'S
AVG 0.02 G'S RMS 0.07 G'S
TIME-SEC
ACCELERATION-G'S

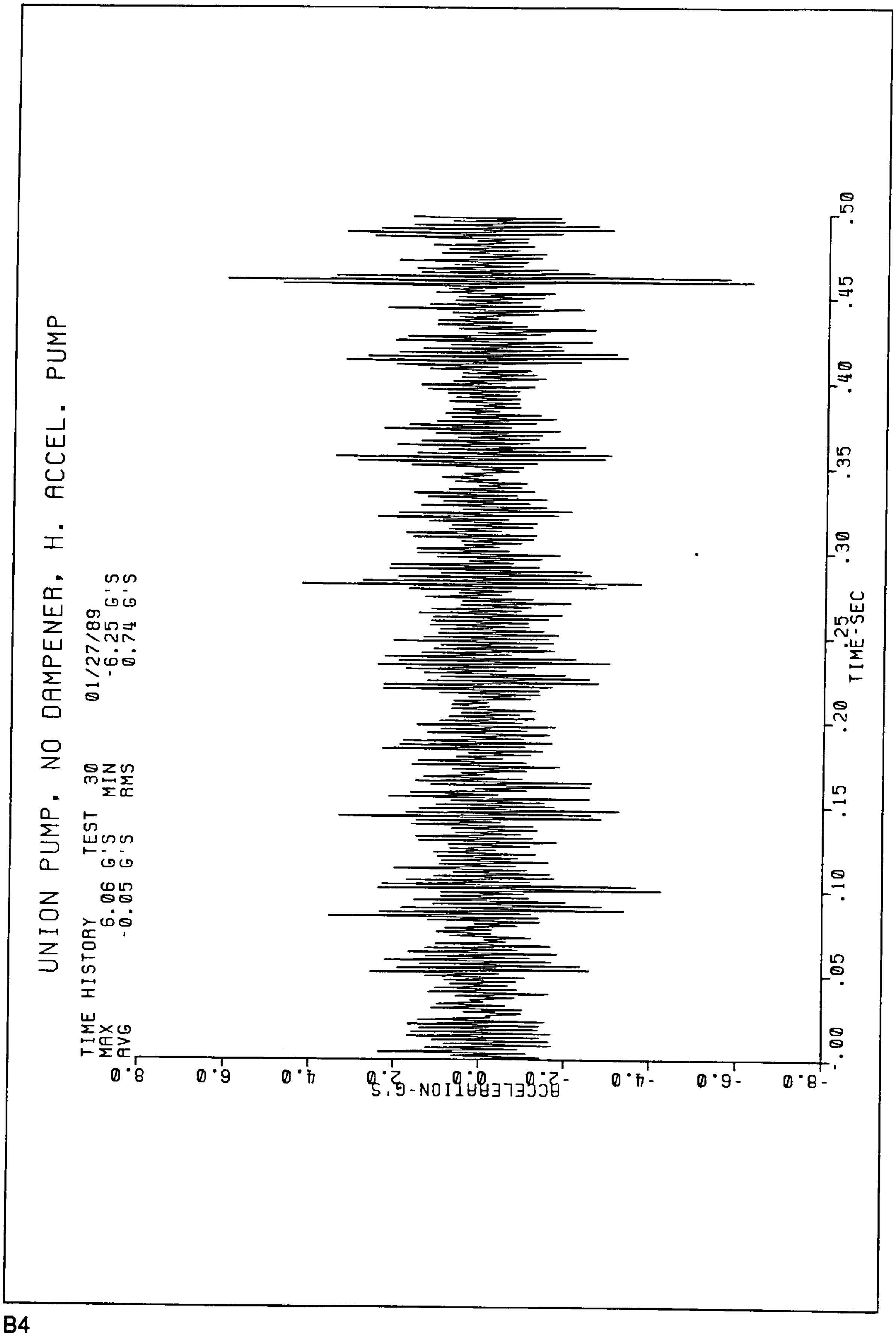

WHEATLEY PUMP, GREER 1 GAL DAMP., V. ACCEL. FL.
TIME HISTORY TEST 15 12/01/88
MAX 1.05 G'S MIN -0.94 G'S
AVG 0.03 G'S RMS 0.12 G'S
TIME-SEC
ACCELERATION-G'S

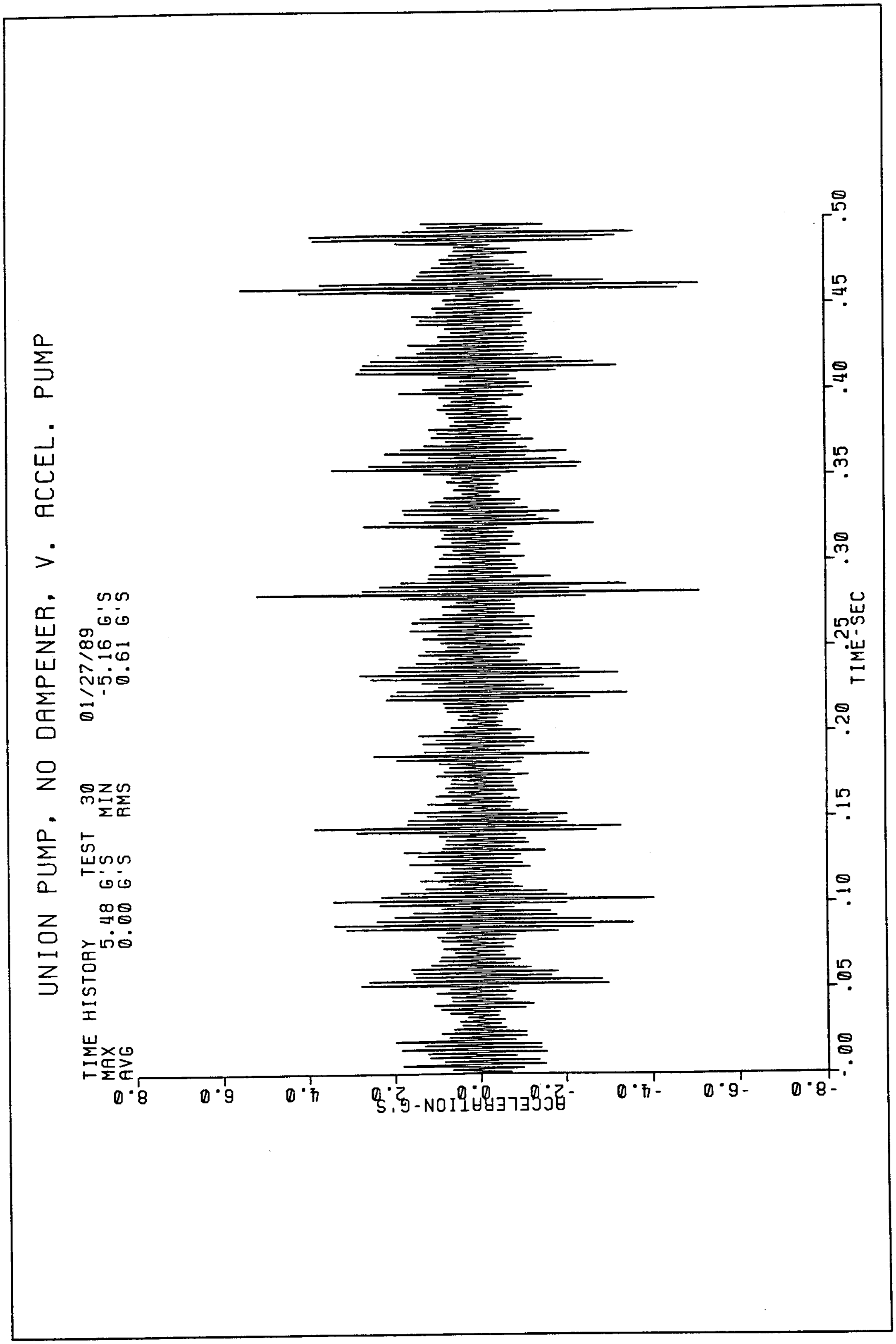
Appendix B
Union Pump

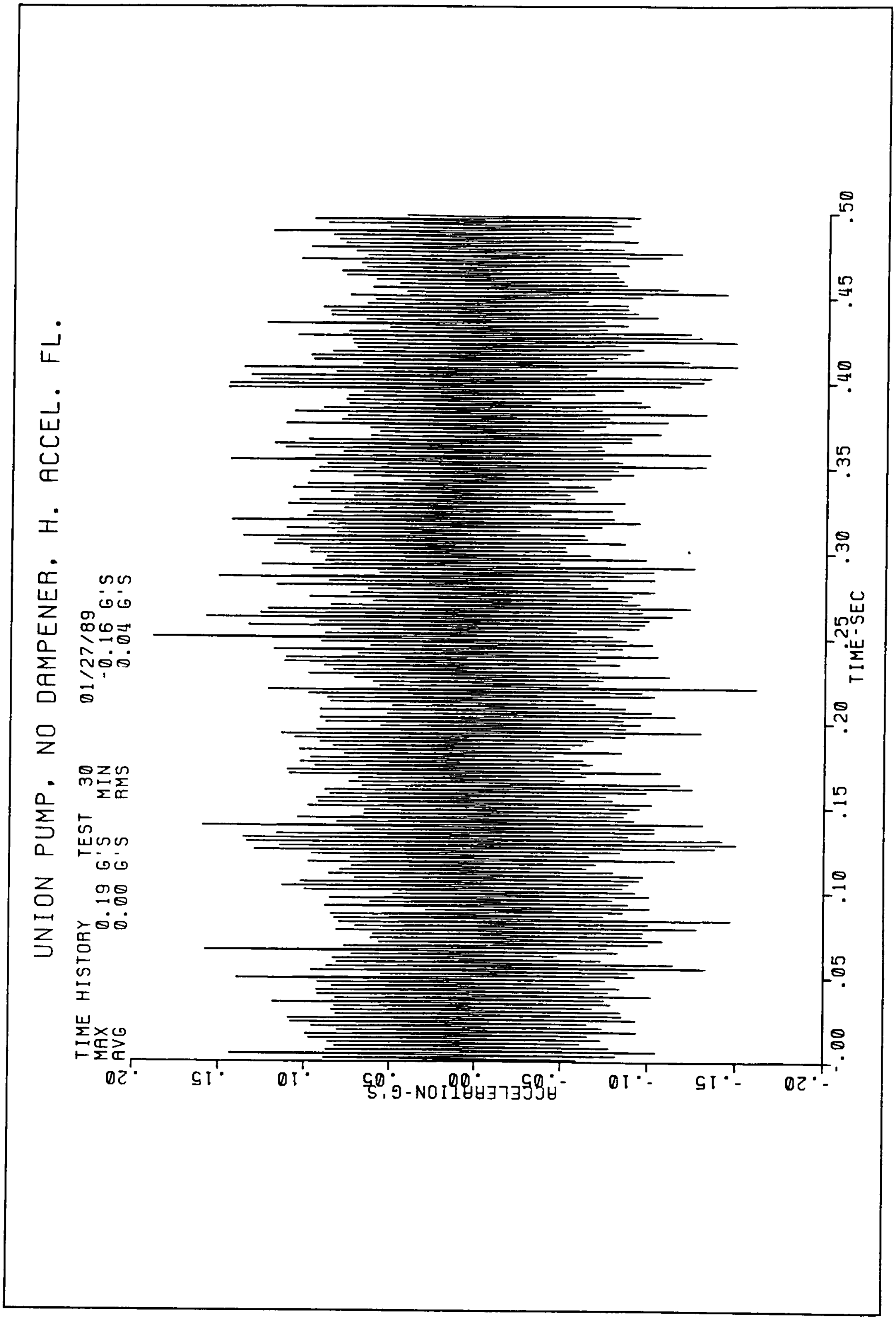
No Pulsation Dampener

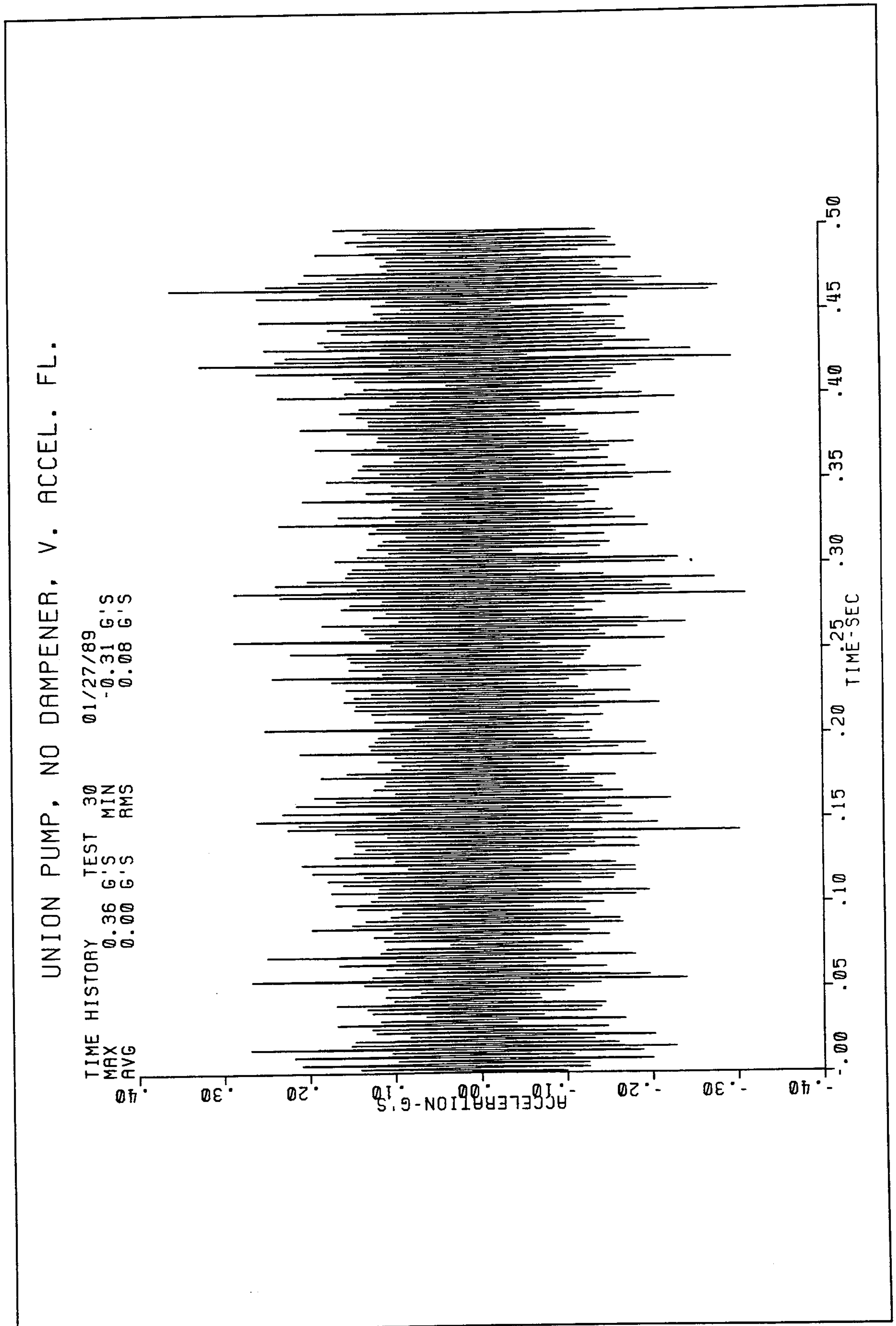

UNION PUMP, NO DAMPENER, OUTPUT PRESSURE
TIME HISTORY TEST 30 01/27/89
MAX 1167.83 PSI MIN 905.87 PSI
AVG 1045.20 PSI RMS 60.97 PSI
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
PRESSURE-PSI
X10¹
0.
20.
40.
60.
80.
100.
120.
140.
160.


UNION PUMP, NO DAMPENER, INPUT PRESSURE
TIME HISTORY TEST 30 01/27/89
MAX 142.53 PSI MIN -8.24 PSI
AVG 31.96 PSI RMS 36.29 PSI
PRESSURE-PSI
160. 120. 80. 40. 0. -40. -80. -120. -160.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


UNION PUMP, NO DAMPENER, H. ACCEL. PUMP
TIME HISTORY TEST 30 01/27/89
MAX 6.06 G'S MIN -6.25 G'S
AVG -0.05 G'S RMS 0.74 G'S
TIME-SEC
ACCELERATION-G'S

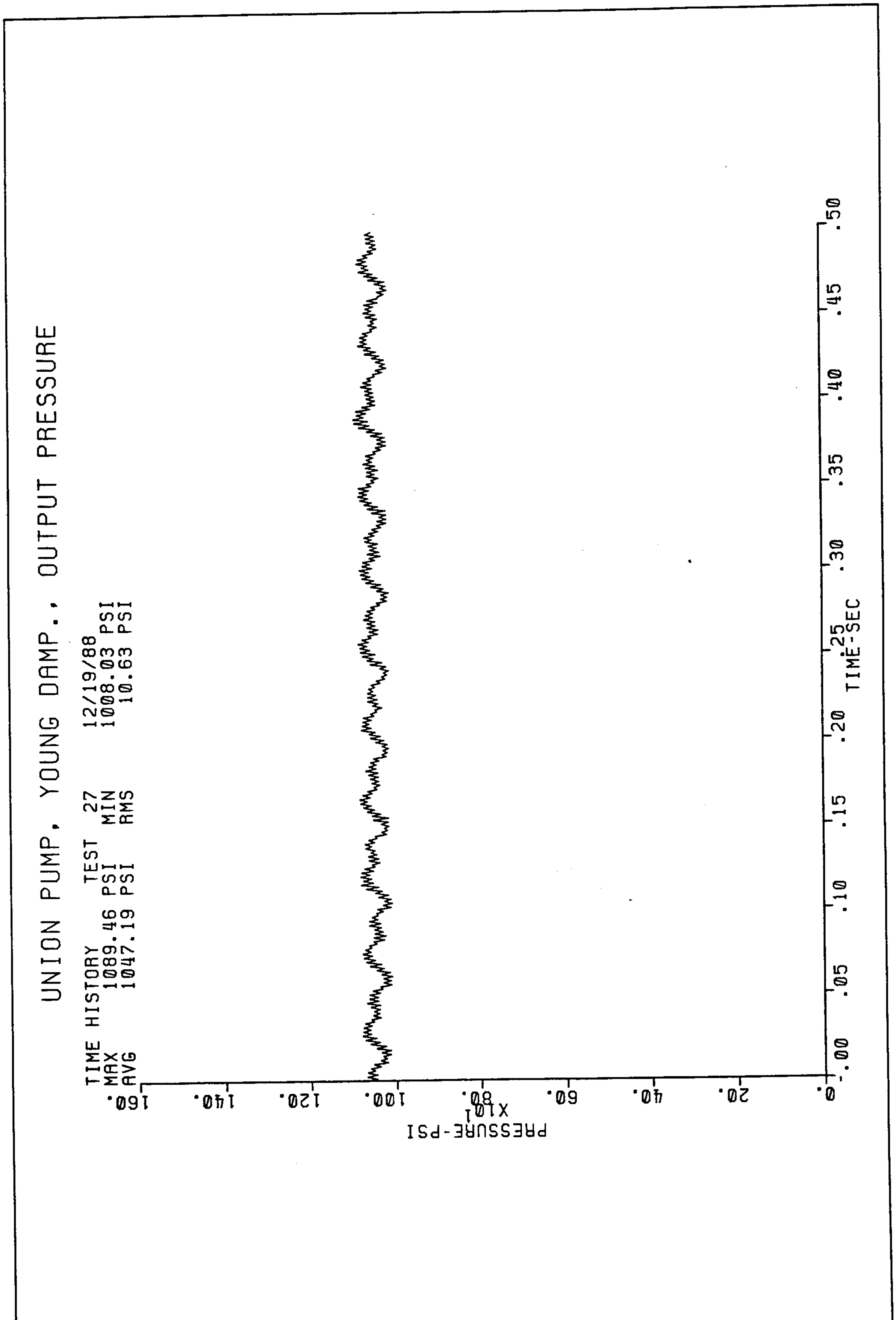

UNION PUMP, NO DAMPENER, V. ACCEL. PUMP
TIME HISTORY TEST 30 01/27/89
MAX 5.48 G'S MIN -5.16 G'S
AVG 0.00 G'S RMS 0.61 G'S
TIME-SEC
ACCELERATION-G'S

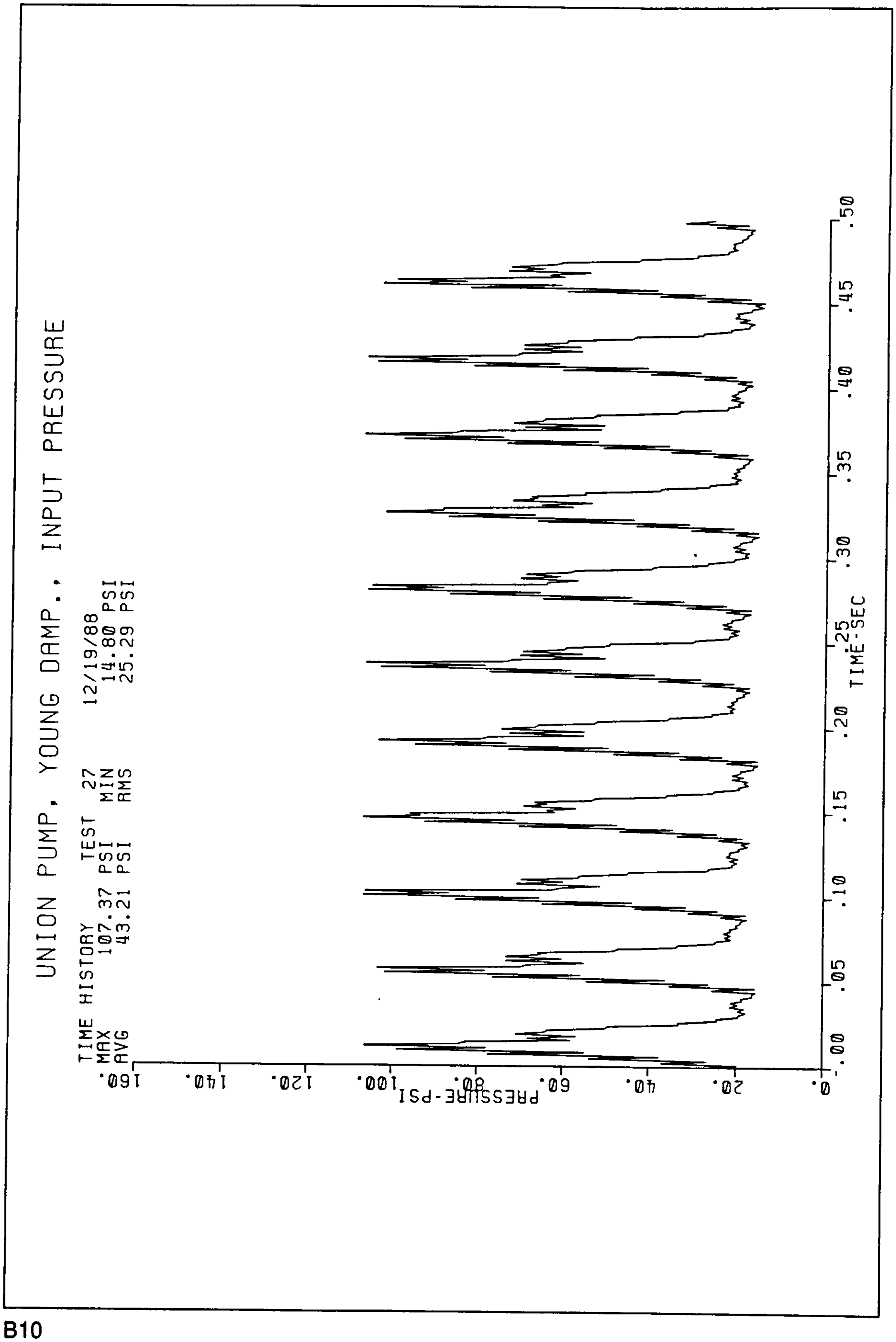

UNION PUMP, NO DAMPENER, H. ACCEL. FL.
TIME HISTORY TEST 30 01/27/89
MAX 0.19 G'S MIN -0.16 G'S
AVG 0.00 G'S RMS 0.04 G'S
TIME-SEC
ACCELERATION-G'S



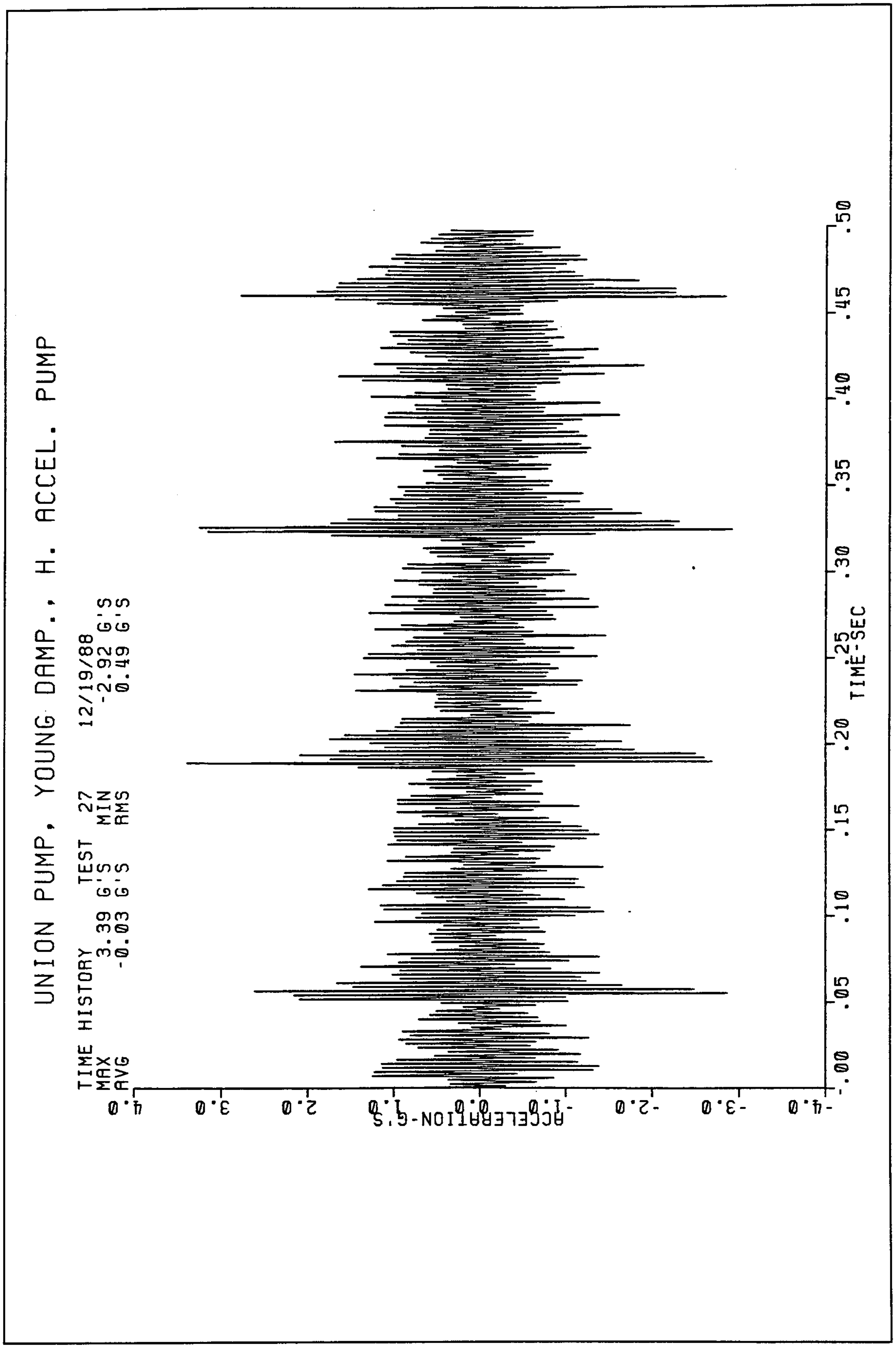
UNION PUMP, NO DAMPENER, V. ACCEL. FL.
TIME HISTORY TEST 30 01/27/89
MAX 0.36 G'S MIN -0.31 G'S
AVG 0.00 G'S RMS 0.08 G'S
TIME-SEC
ACCELERATION-G'S

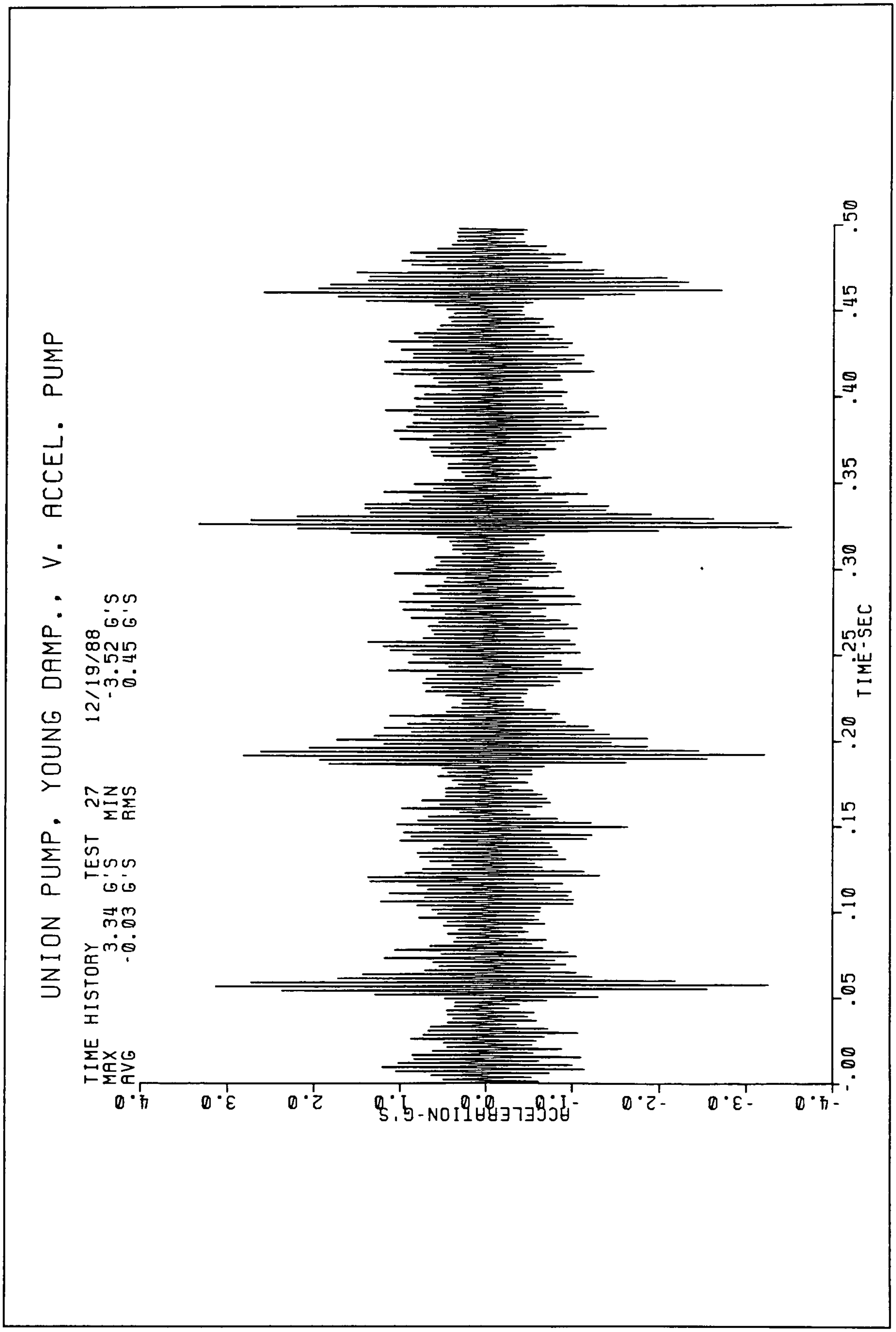
Young Engineering Pulsation Dampener

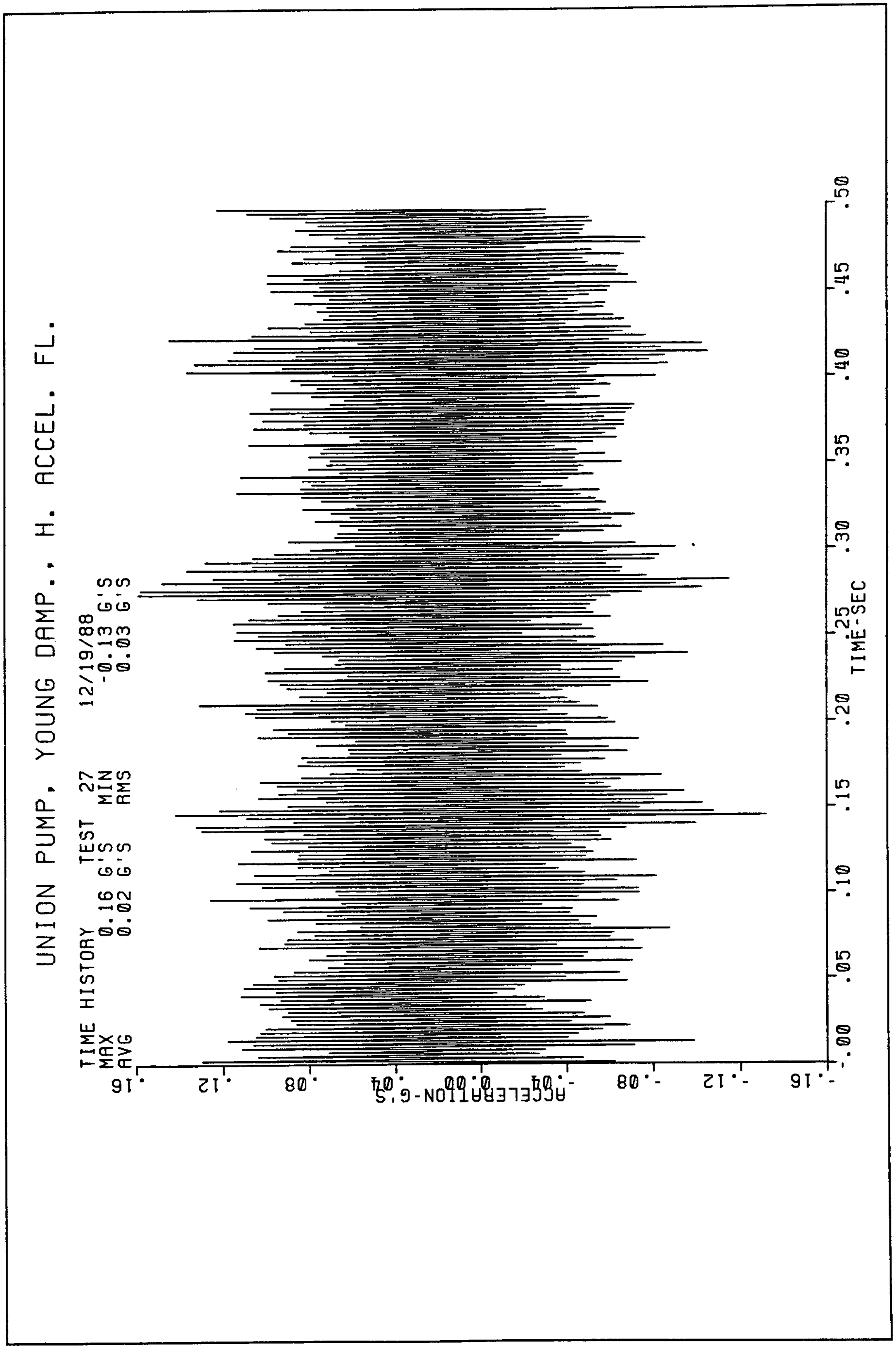

UNION PUMP, YOUNG DAMP., OUTPUT PRESSURE
TIME HISTORY TEST 27 12/19/88
MAX 1089.46 PSI MIN 1008.03 PSI
AVG 1047.19 PSI RMS 10.63 PSI
PRESSURE-PSI
X10[1]
0. 20. 40. 60. 80. 100. 120. 140. 160.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


UNION PUMP, YOUNG DAMP., INPUT PRESSURE
TIME HISTORY TEST 27 12/19/88
MAX 107.37 PSI MIN 14.80 PSI
AVG 43.21 PSI RMS 25.29 PSI
PRESSURE-PSI
TIME-SEC
0. 20. 40. 60. 80. 100. 120. 140. 160.
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

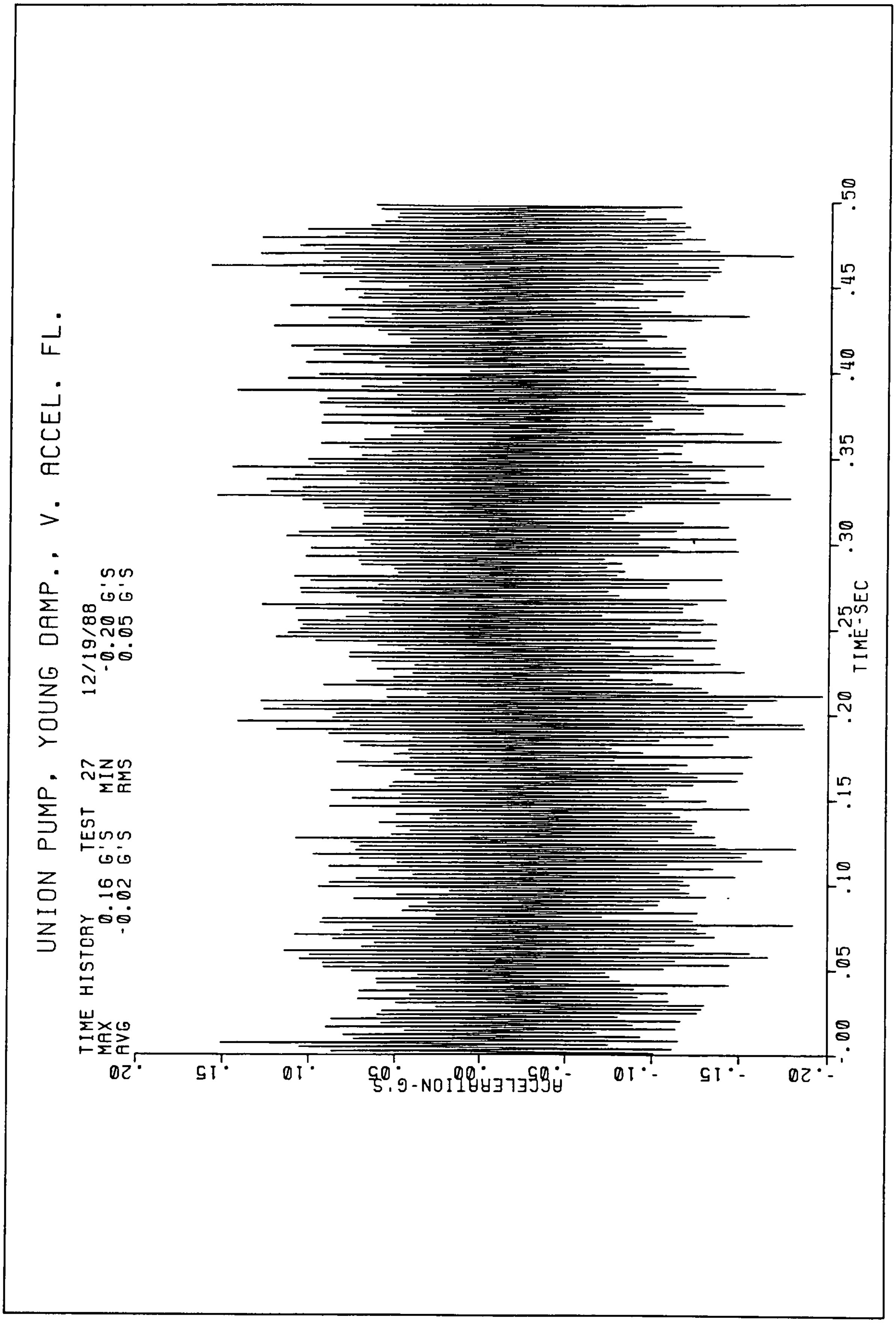
B10


UNION PUMP, YOUNG DAMP., H. ACCEL. PUMP
TIME HISTORY TEST 27 12/19/88
MAX 3.39 G'S MIN -2.92 G'S
AVG -0.03 G'S RMS 0.49 G'S
ACCELERATION-G'S
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50


UNION PUMP, YOUNG DAMP., V. ACCEL. PUMP
TIME HISTORY TEST 27 12/19/88
MAX 3.34 G'S MIN -3.52 G'S
AVG -0.03 G'S RMS 0.45 G'S
ACCELERATION-G'S
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

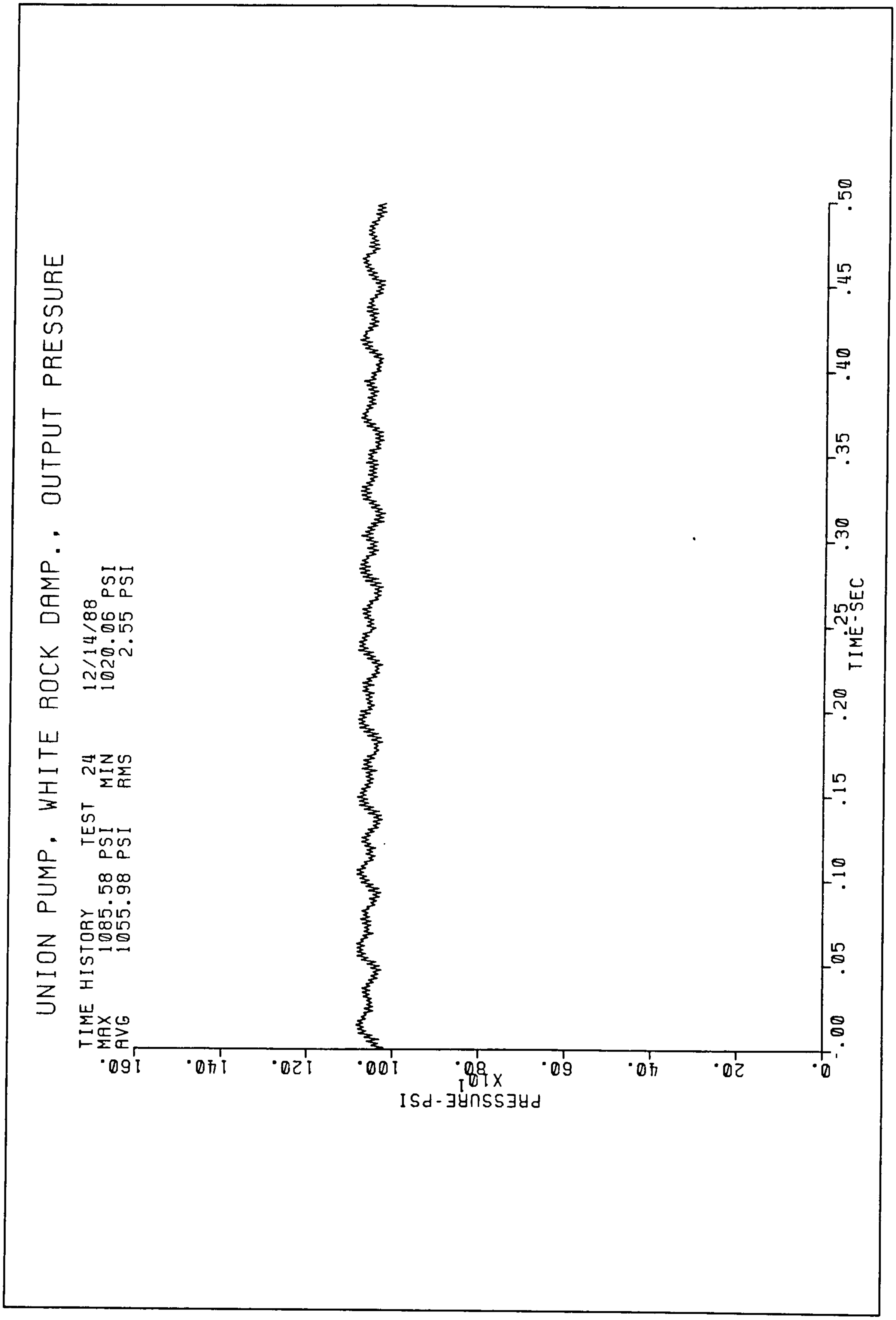


UNION PUMP, YOUNG DAMP., H. ACCEL. FL.
TIME HISTORY TEST 27 12/19/88
MAX 0.16 G'S MIN -0.13 G'S
AVG 0.02 G'S RMS 0.03 G'S
TIME-SEC
ACCELERATION-G'S

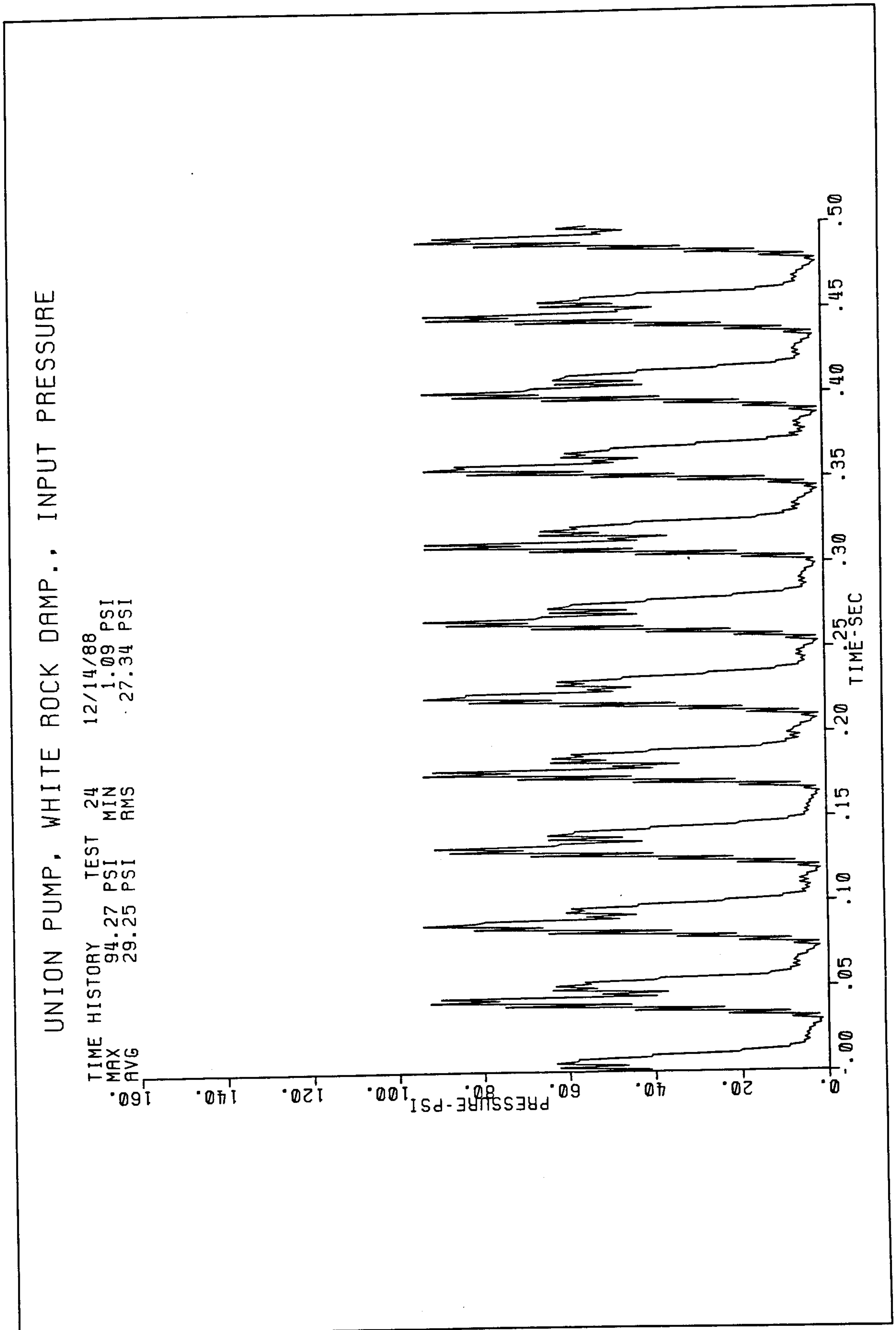


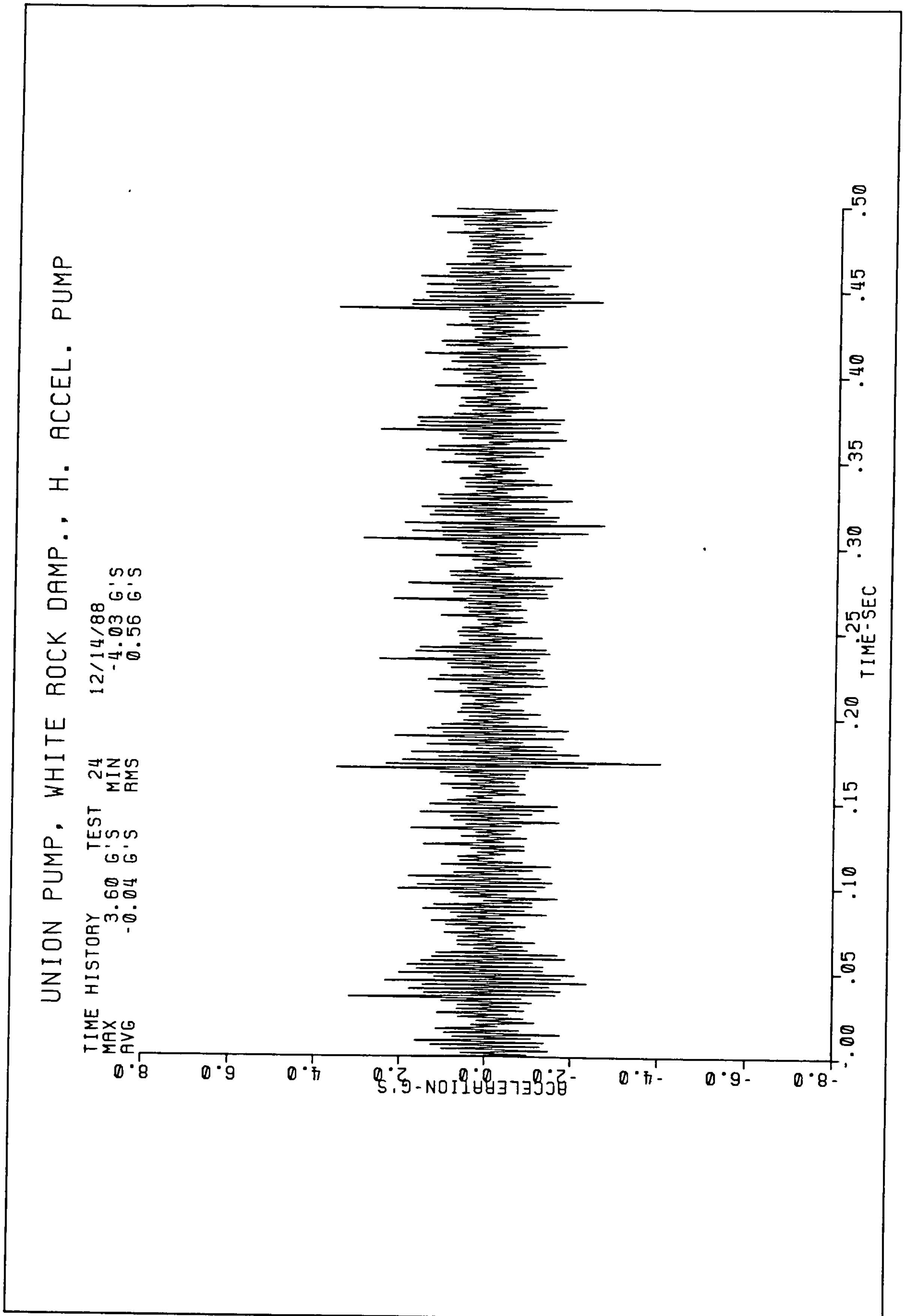
UNION PUMP, YOUNG DAMP., V. ACCEL. FL.
TIME HISTORY TEST 27 12/19/88
MAX 0.16 G'S MIN -0.20 G'S
AVG -0.02 G'S RMS 0.05 G'S
ACCELERATION-G'S
.20
.15
.10
.05
.00
-.05
-.10
-.15
-.20
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50

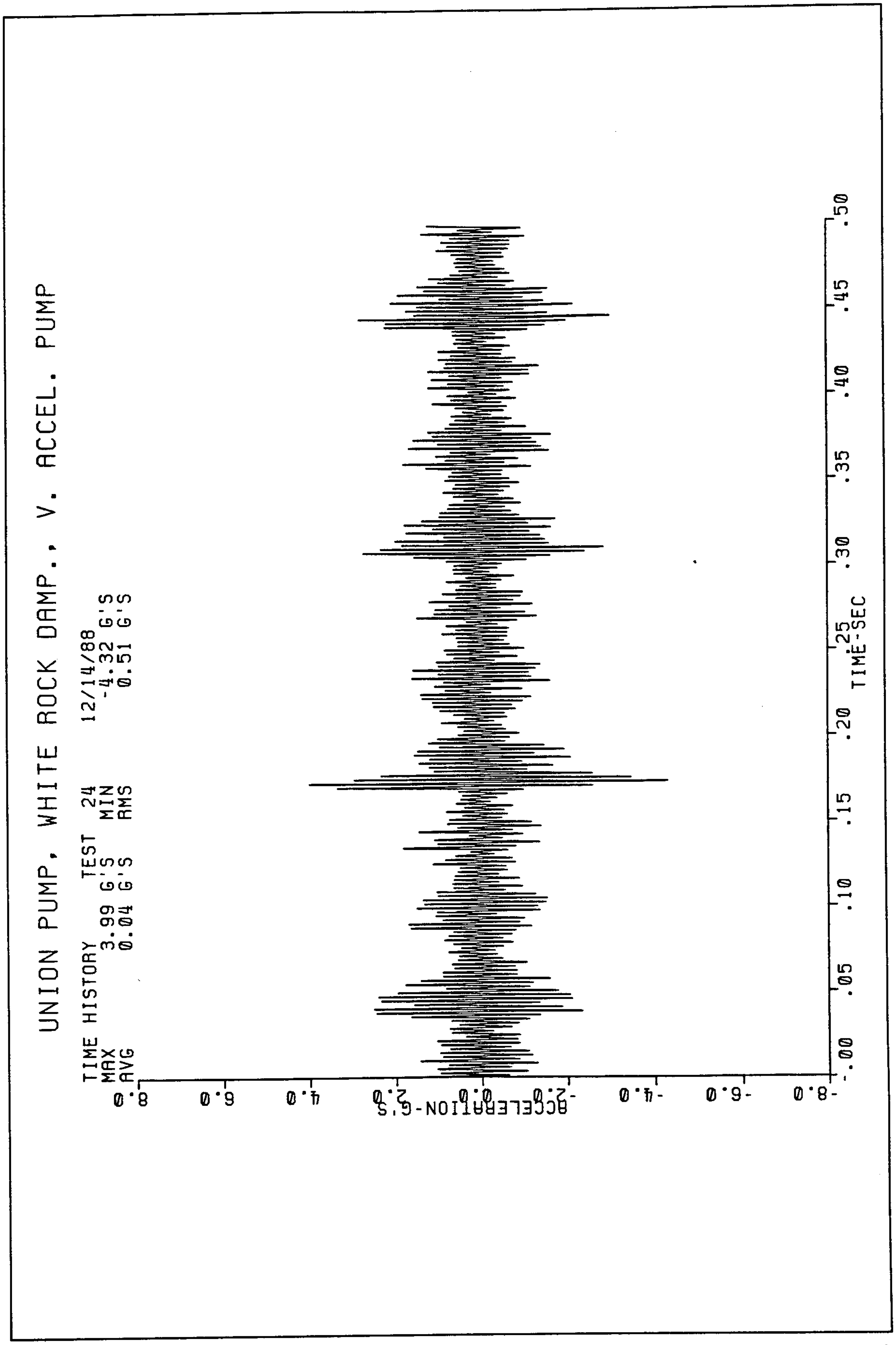
White Rock Pulsation Dampener



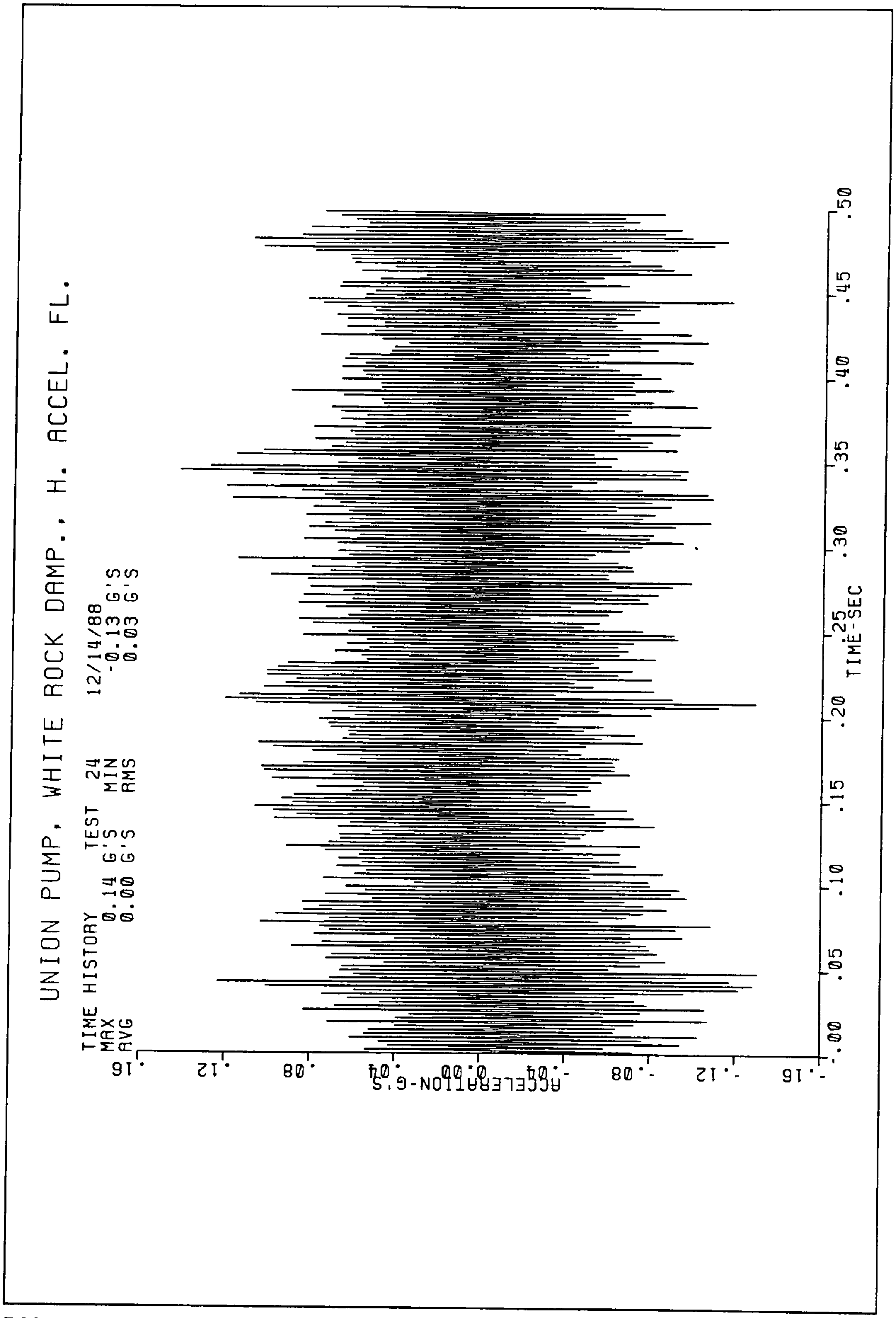
UNION PUMP, WHITE ROCK DAMP., OUTPUT PRESSURE
TIME HISTORY TEST 24 12/14/88
MAX 1085.58 PSI MIN 1020.06 PSI
AVG 1055.98 PSI RMS 2.55 PSI
PRESSURE-PSI
X10 1
0. 20. 40. 60. 80. 100. 120. 140. 160.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

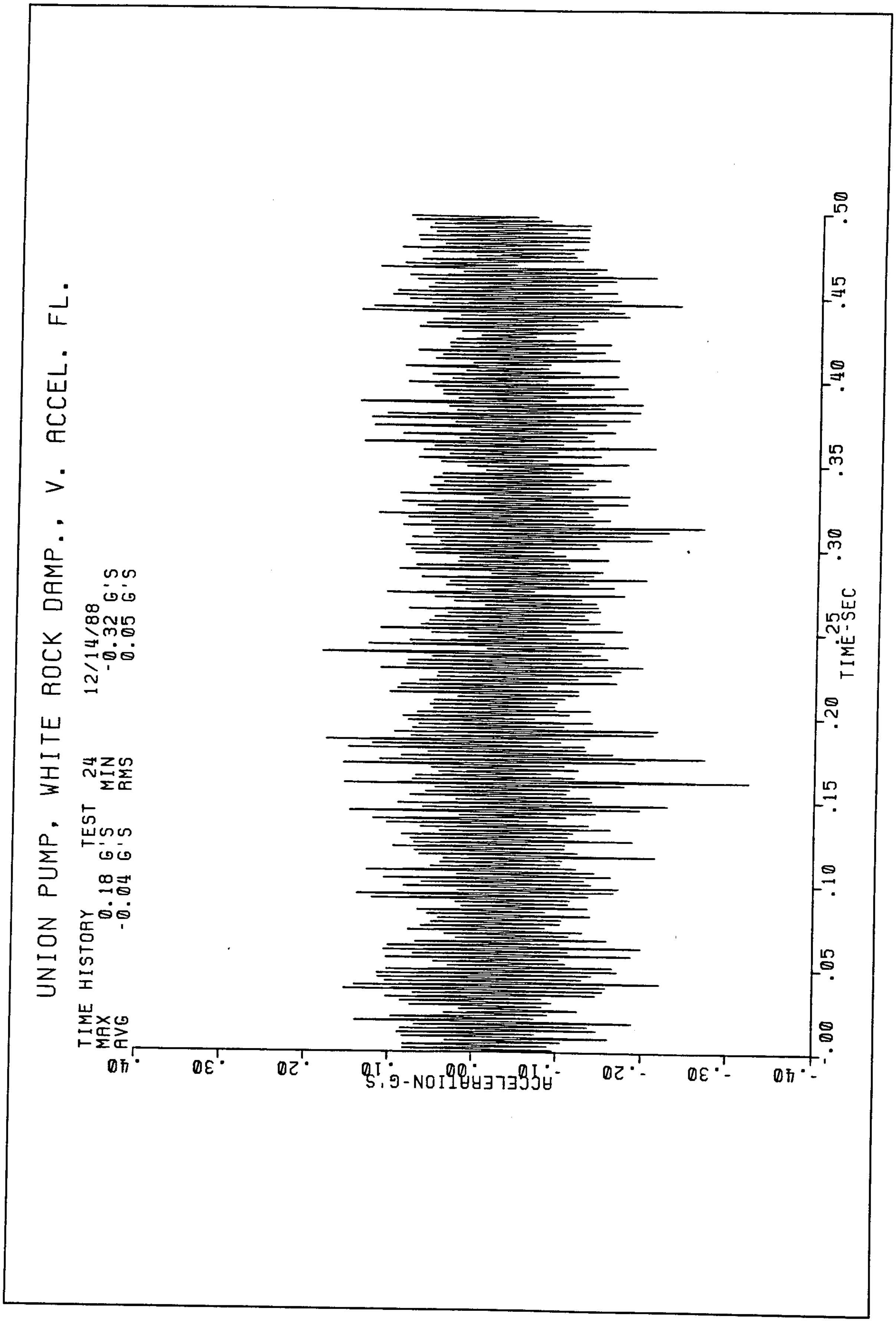

UNION PUMP, WHITE ROCK DAMP., INPUT PRESSURE
TIME HISTORY TEST 24 12/14/88
MAX 94.27 PSI MIN 1.09 PSI
AVG 29.25 PSI RMS 27.34 PSI
PRESSURE-PSI
0. 20. 40. 60. 80. 100. 120. 140. 160.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


UNION PUMP, WHITE ROCK DAMP., H. ACCEL. PUMP
TIME HISTORY TEST 24 12/14/88
MAX 3.60 G'S MIN -4.03 G'S
AVG -0.04 G'S RMS 0.56 G'S
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
ACCELERATION-G'S
8.0 6.0 4.0 2.0 0.0 -2.0 -4.0 -6.0 -8.0

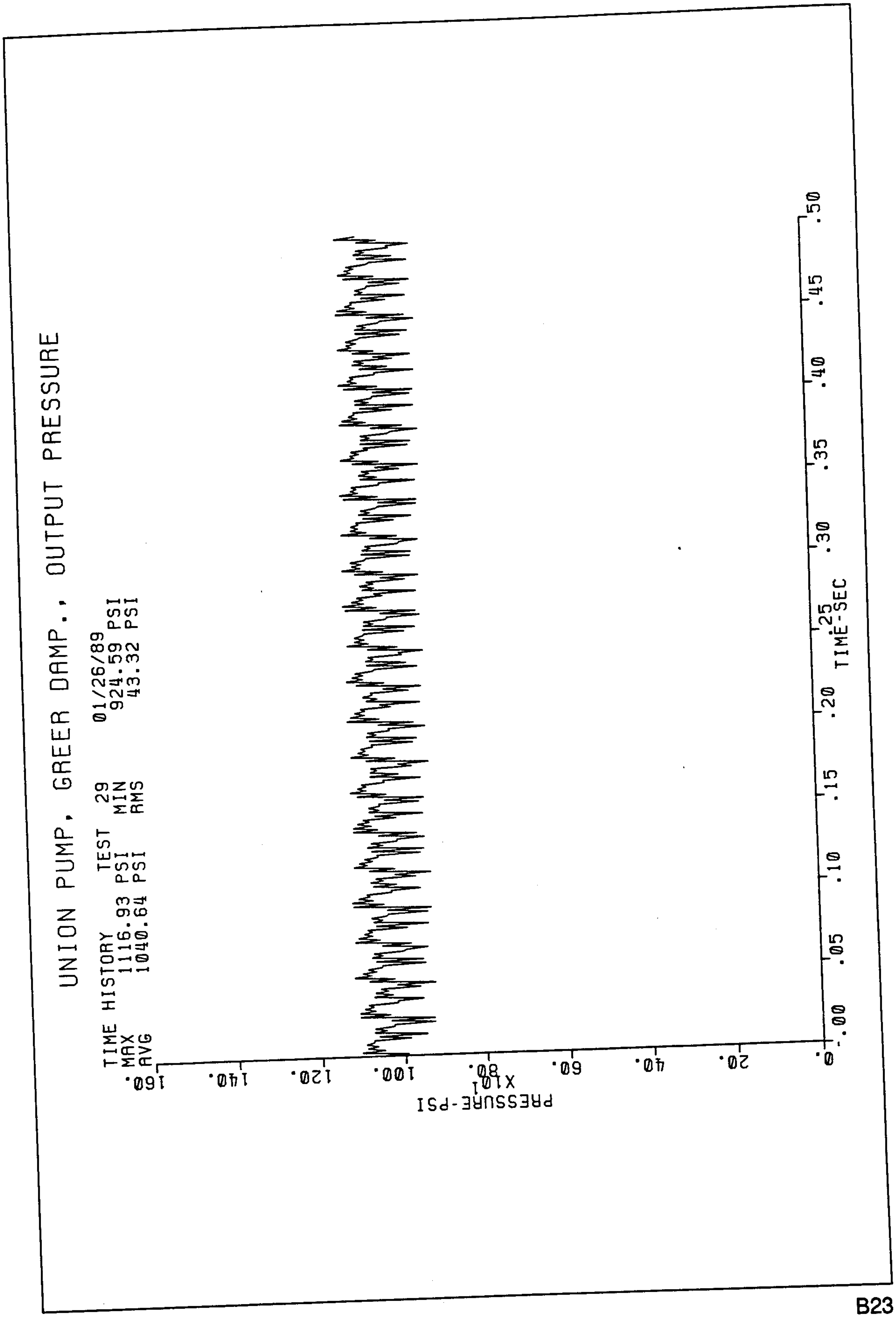


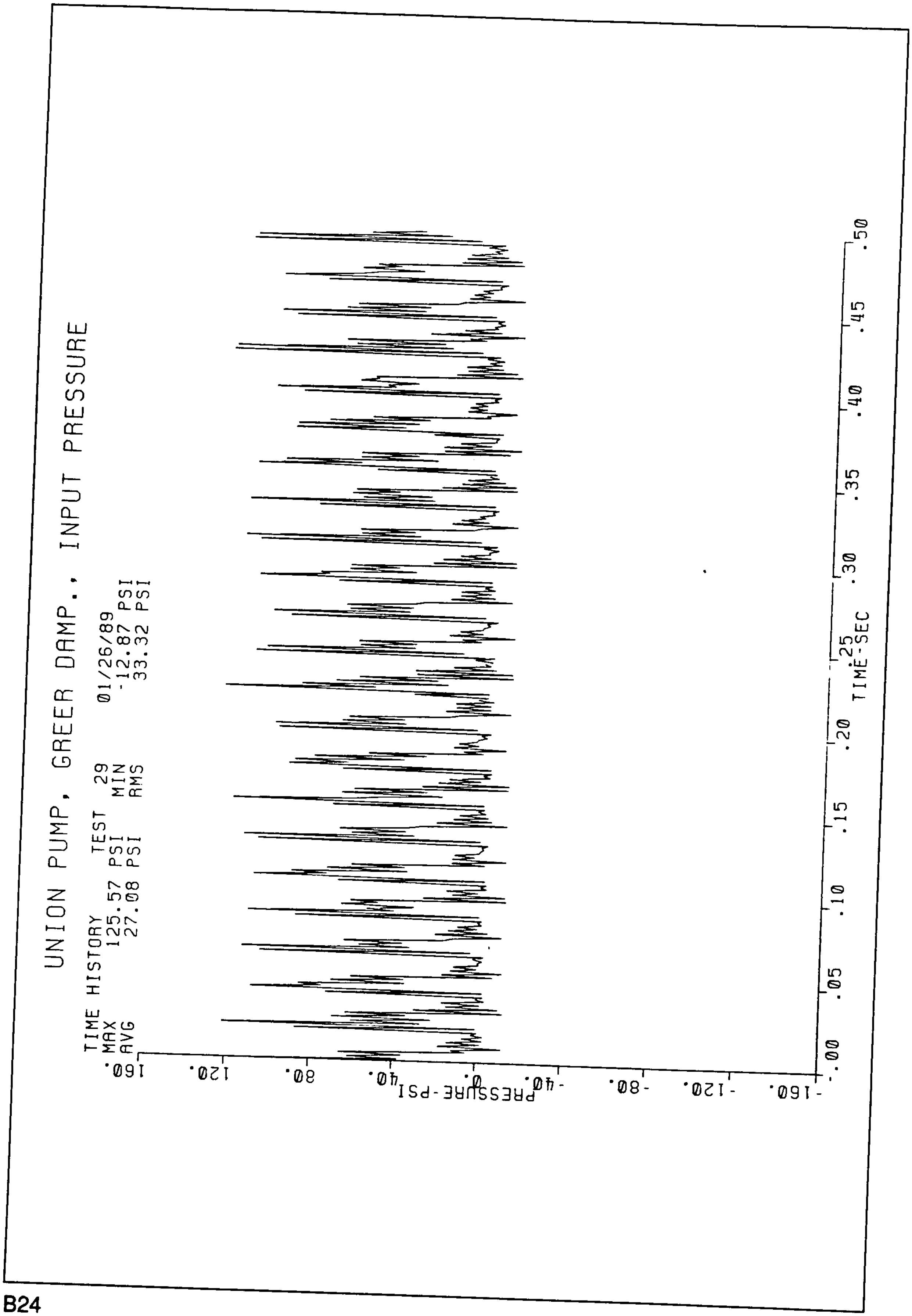
UNION PUMP, WHITE ROCK DAMP., V. ACCEL. PUMP
TIME HISTORY TEST 24 12/14/88
MAX 3.99 G'S MIN -4.32 G'S
AVG 0.04 G'S RMS 0.51 G'S
TIME-SEC
ACCELERATION-G'S
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
8.0 6.0 4.0 2.0 0.0 -2.0 -4.0 -6.0 -8.0

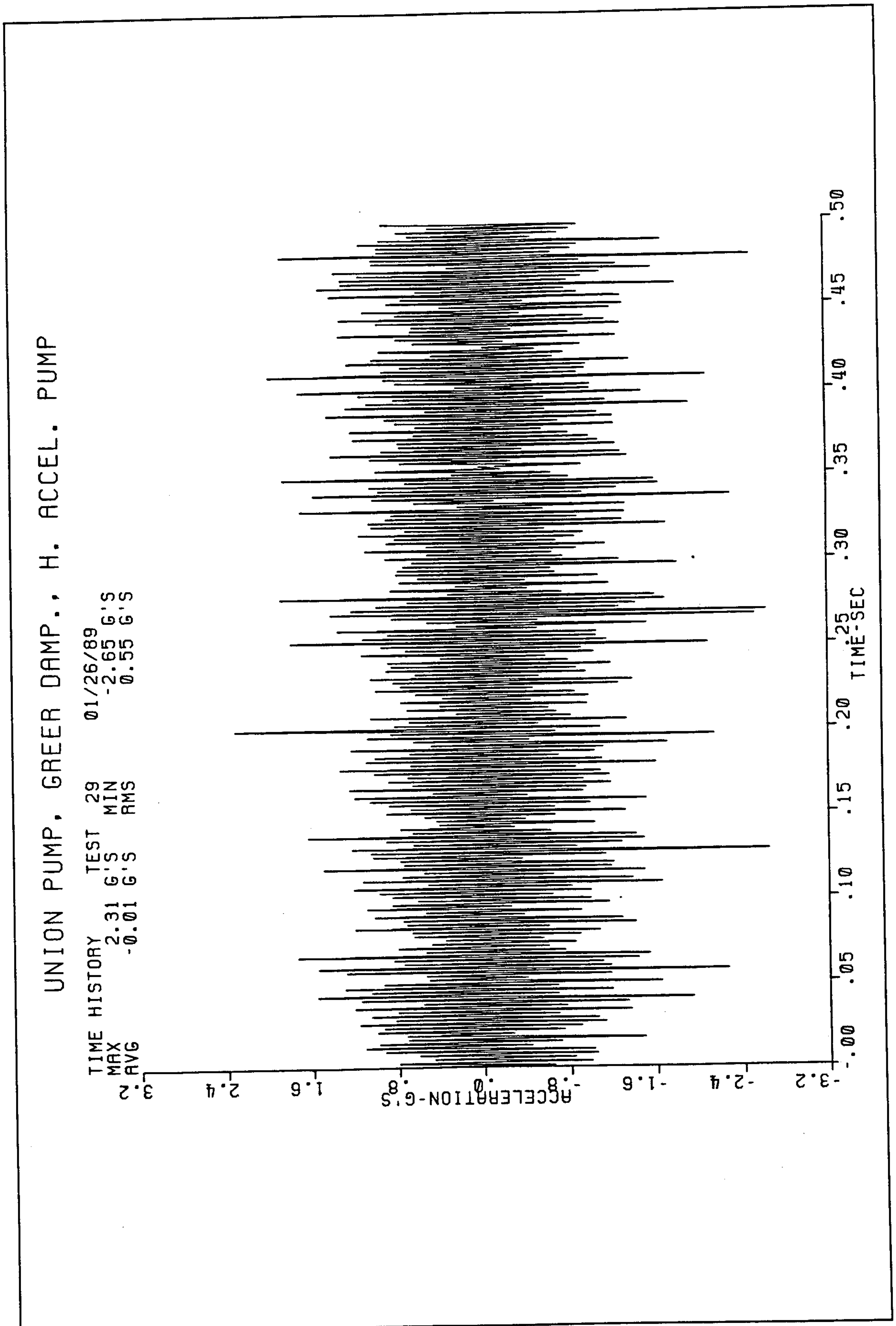

UNION PUMP, WHITE ROCK DAMP., H. ACCEL. FL.
TIME HISTORY TEST 24 12/14/88
MAX 0.14 G'S MIN -0.13 G'S
AVG 0.00 G'S RMS 0.03 G'S
TIME-SEC
ACCELERATION-G'S
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
.16 .12 .08 .04 0.00 -.04 -.08 -.12 -.16

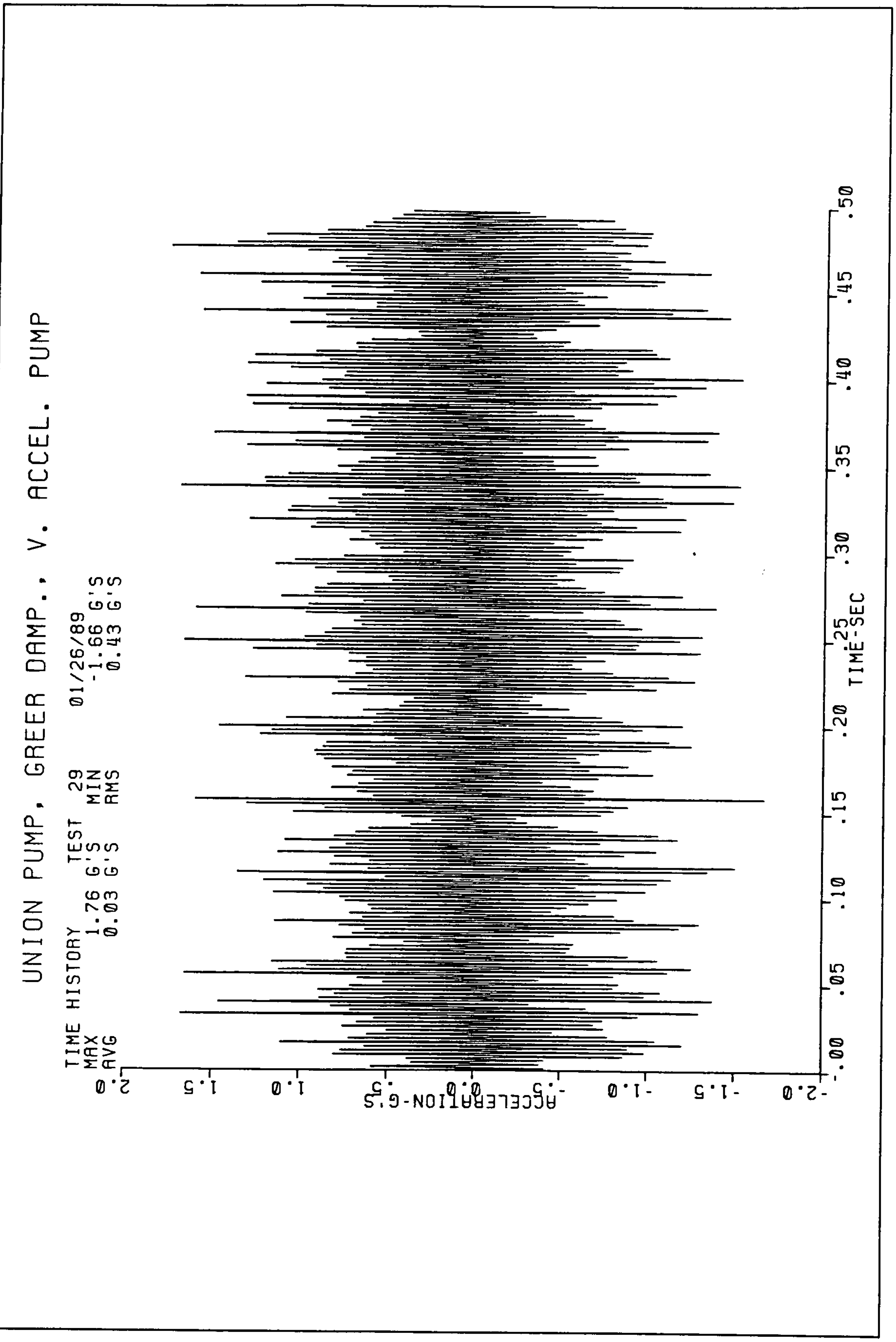

UNION PUMP, WHITE ROCK DAMP., V. ACCEL. FL.
TIME HISTORY TEST 24 12/14/88
MAX 0.18 G'S MIN -0.32 G'S
AVG -0.04 G'S RMS 0.05 G'S
TIME-SEC
ACCELERATION-G'S

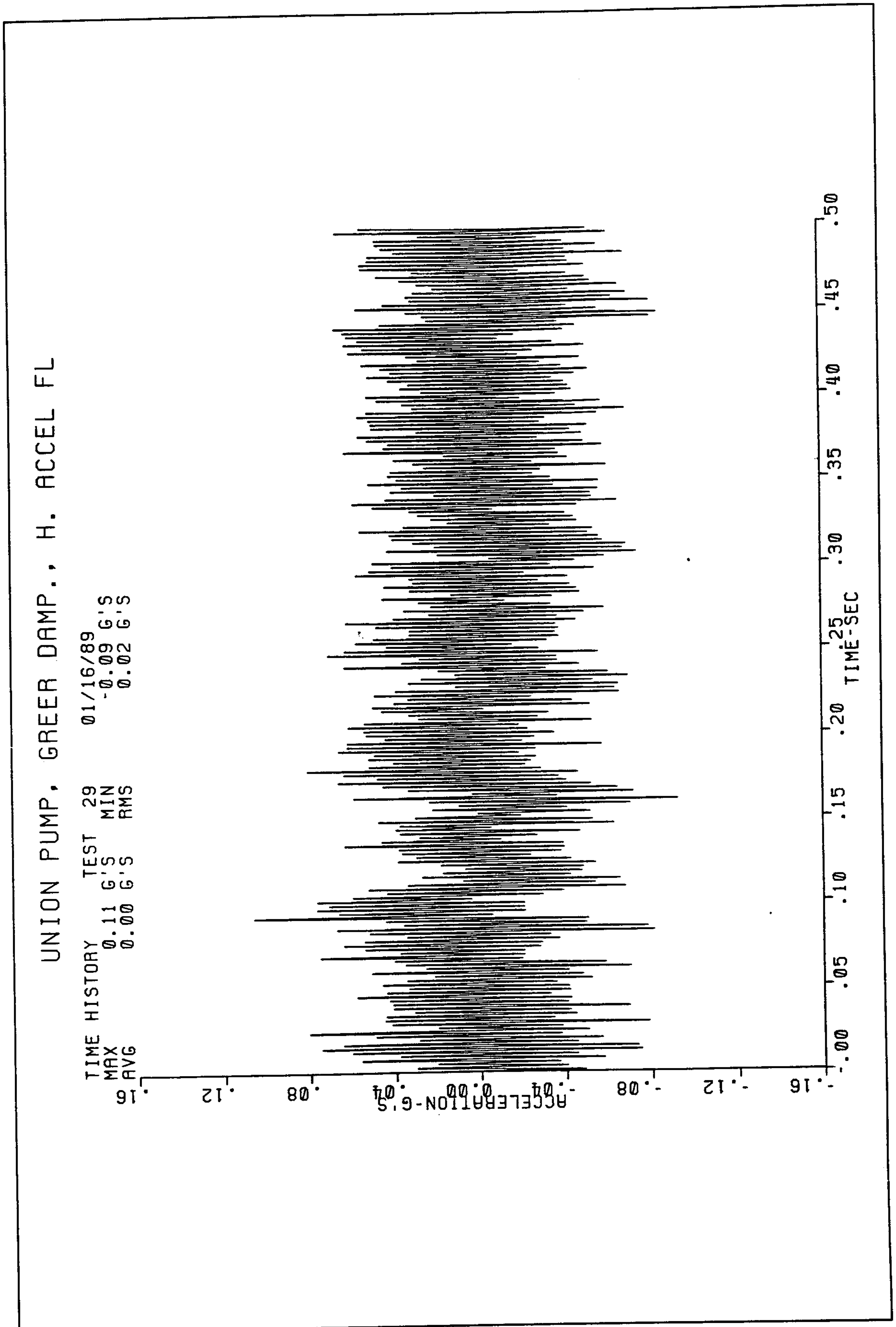
Greer 1-Gal (4-Qt) Pulsation Dampener

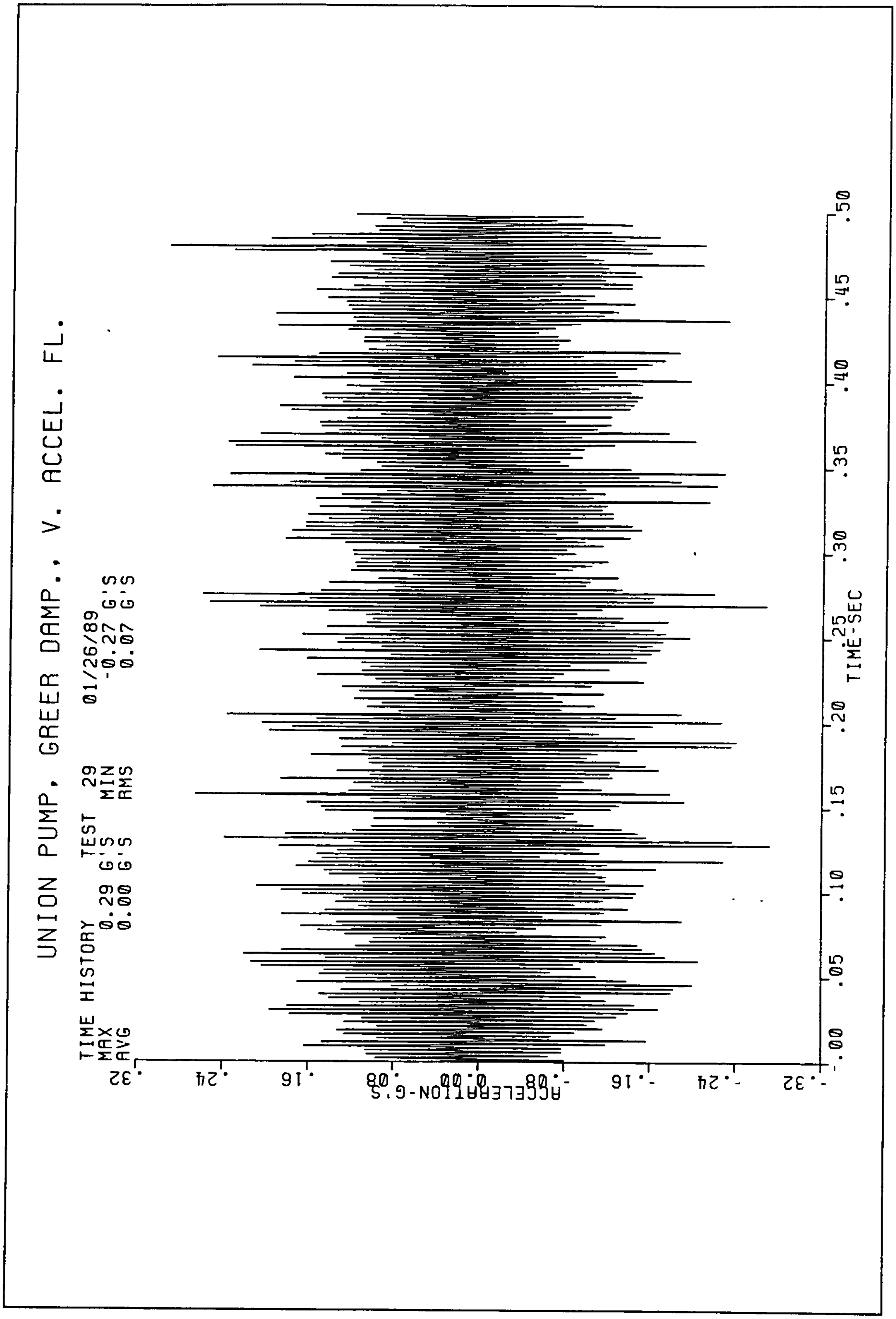

UNION PUMP, GREER DAMP., OUTPUT PRESSURE
TIME HISTORY TEST 29 01/26/89
MAX 1116.93 PSI MIN 924.59 PSI
AVG 1040.64 PSI RMS 43.32 PSI
160.
140.
120.
100.
80.
60.
40.
20.
0.
X10^1
PRESSURE-PSI
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
TIME-SEC


UNION PUMP, GREER DAMP., INPUT PRESSURE
TIME HISTORY TEST 29 01/26/89
MAX 125.57 PSI MIN -12.87 PSI
AVG 27.08 PSI RMS 33.32 PSI
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
PRESSURE-PSI
160. 120. 80. 40. 0. -40. -80. -120. -160.


UNION PUMP, GREER DAMP., H. ACCEL. PUMP
TIME HISTORY TEST 29 Ø1/26/89
MAX 2.31 G'S MIN -2.65 G'S
AVG -Ø.Ø1 G'S RMS Ø.55 G'S
TIME-SEC
.ØØ .Ø5 .1Ø .15 .2Ø .25 .3Ø .35 .4Ø .45 .5Ø
ACCELERATION-G'S
3.2 2.4 1.6 .8 Ø. -.8 -1.6 -2.4 -3.2

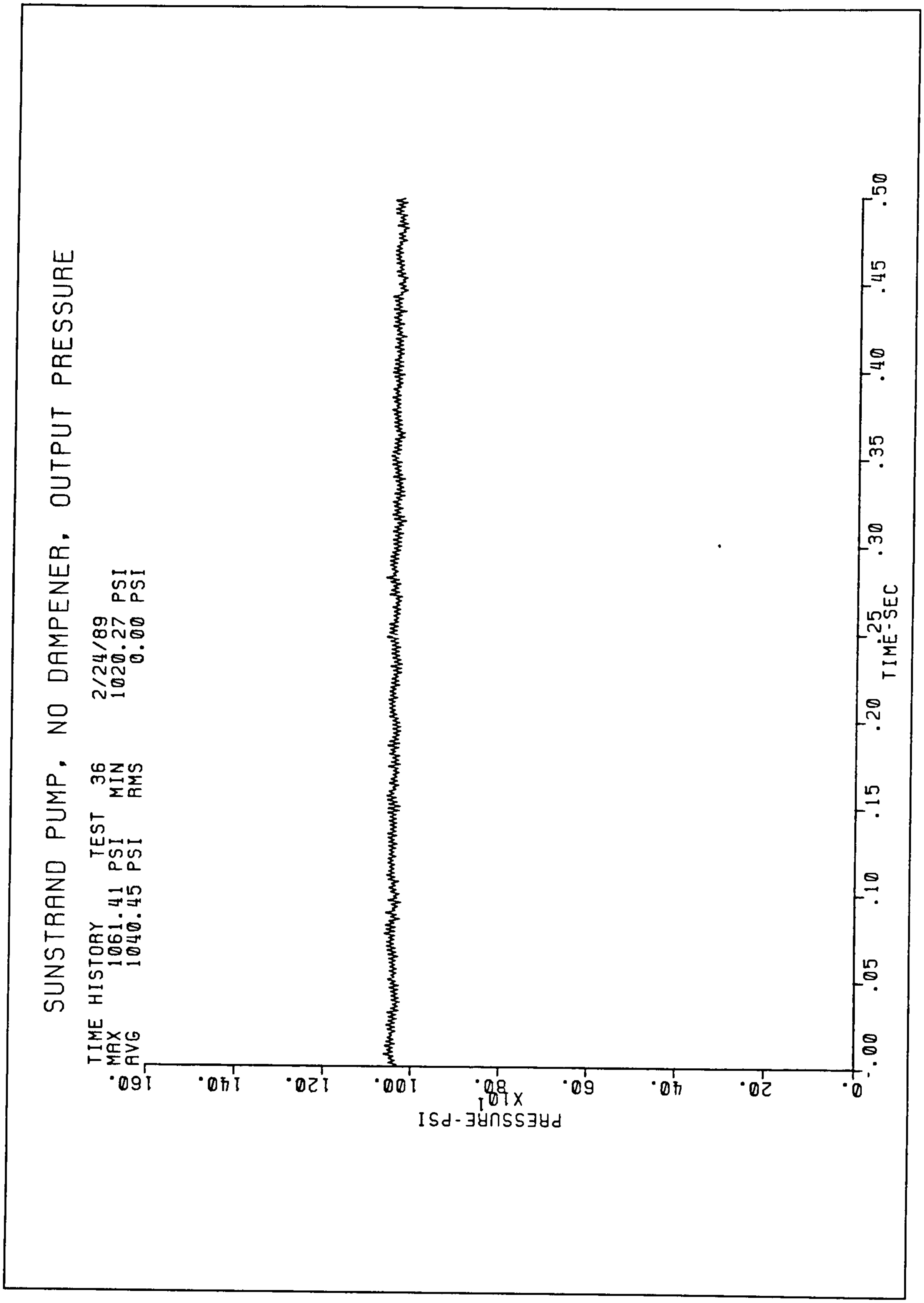

UNION PUMP, GREER DAMP., V. ACCEL. PUMP
TIME HISTORY TEST 29 01/26/89
MAX 1.76 G'S MIN -1.66 G'S
AVG 0.03 G'S RMS 0.43 G'S
ACCELERATION-G'S
2.0 1.5 1.0 .5 0.0 -.5 -1.0 -1.5 -2.0
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


UNION PUMP, GREER DAMP., H. ACCEL FL
TIME HISTORY TEST 29 01/16/89
MAX 0.11 G'S MIN -0.09 G'S
AVG 0.00 G'S RMS 0.02 G'S
ACCELERATION-G'S
.16
.12
.08
.04
0.00
-.04
-.08
-.12
-.16
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50

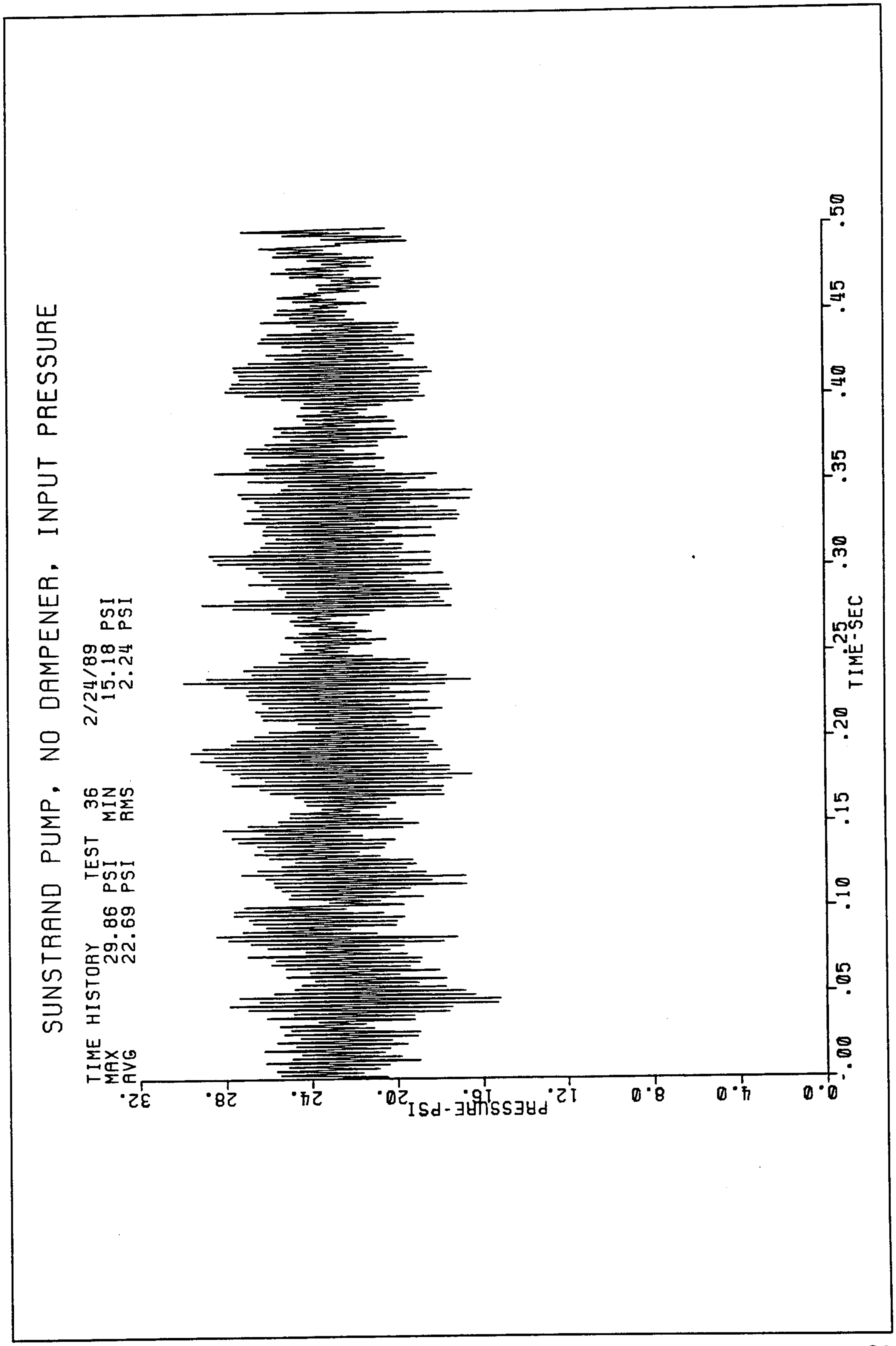

UNION PUMP, GREER DAMP., V. ACCEL. FL.
TIME HISTORY TEST 29 01/26/89
MAX 0.29 G'S MIN -0.27 G'S
AVG 0.00 G'S RMS 0.07 G'S
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
ACCELERATION-G'S
.32 .24 .16 .08 0.00 -.08 -.16 -.24 -.32

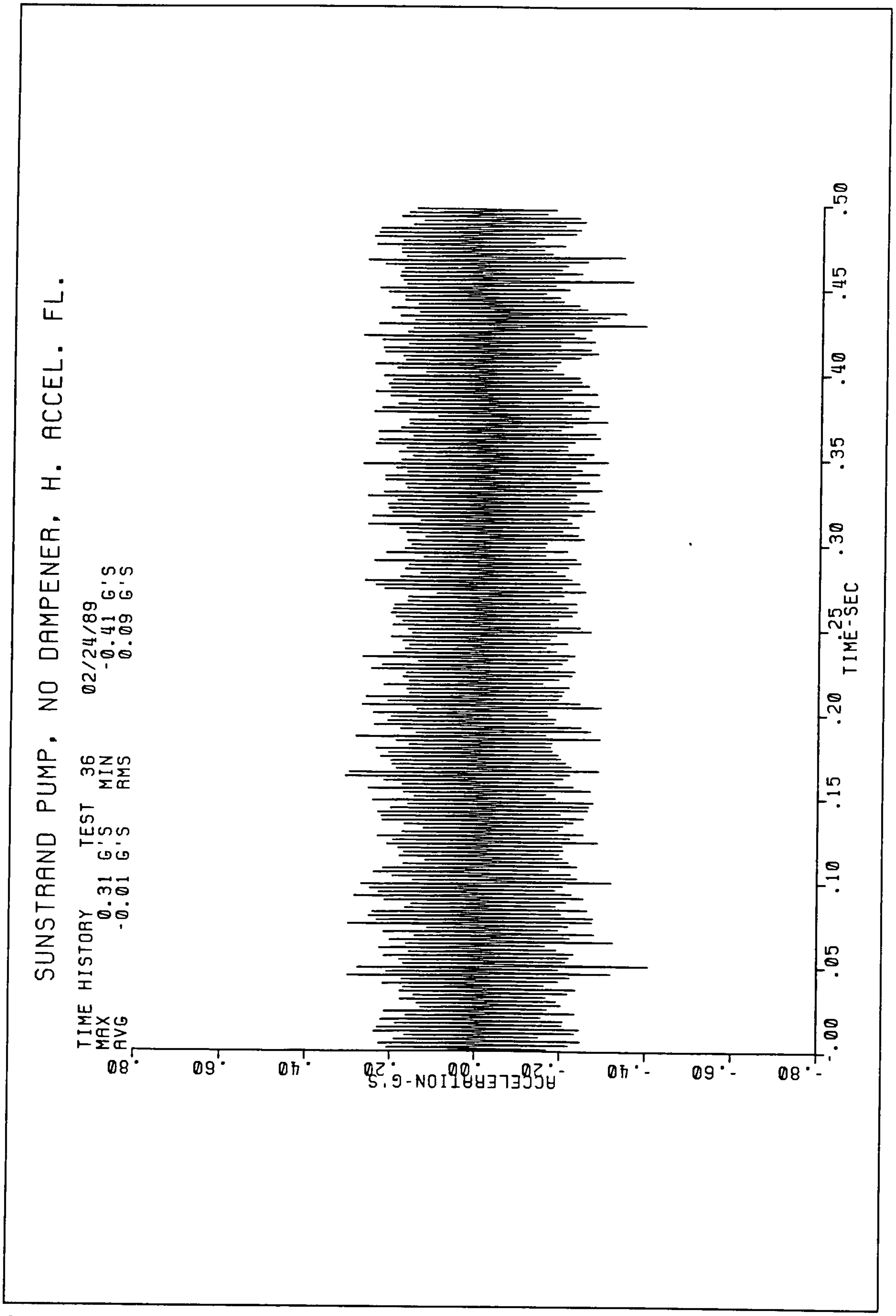
Appendix C
Sundstrand Pump

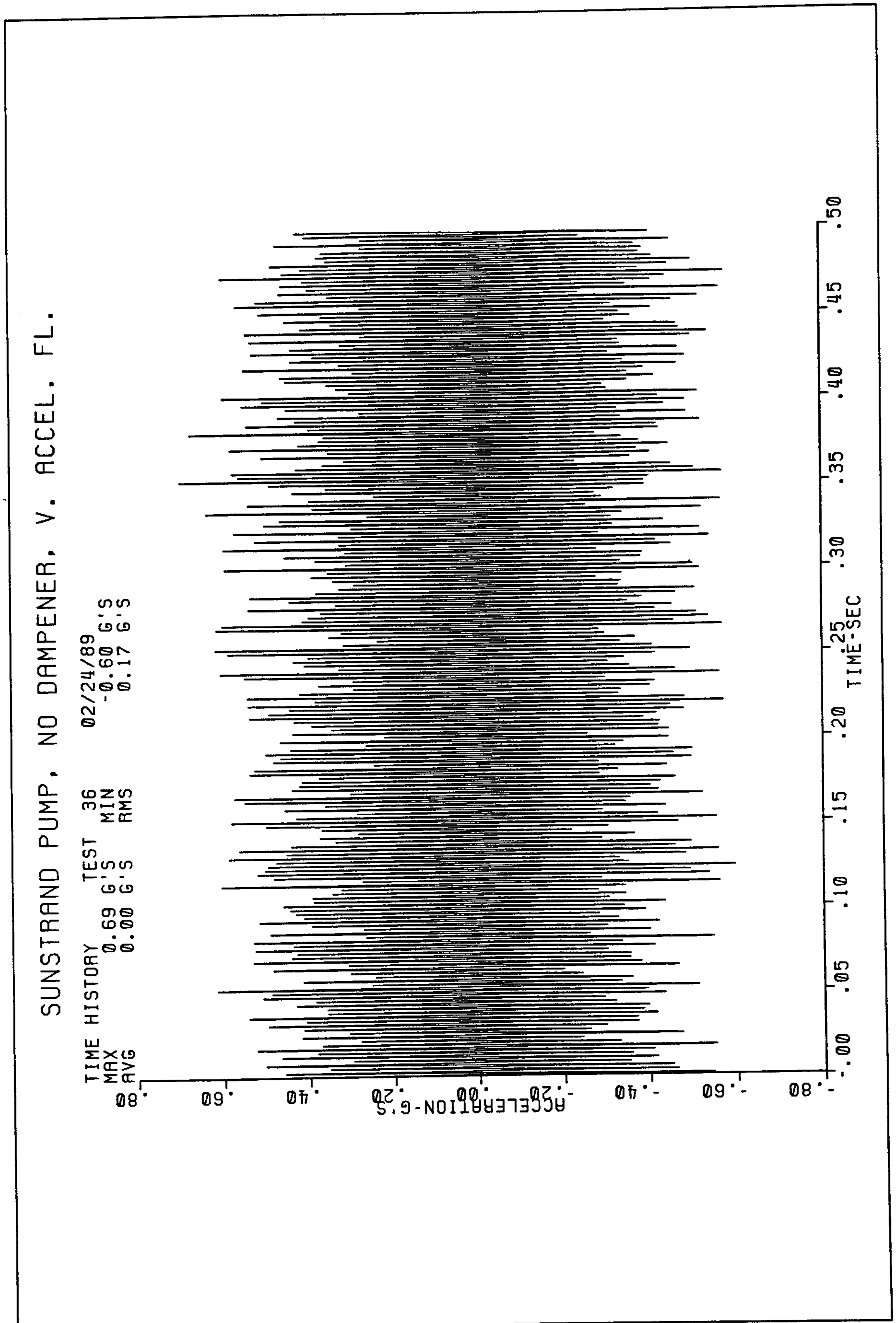
No Pulsation Dampener



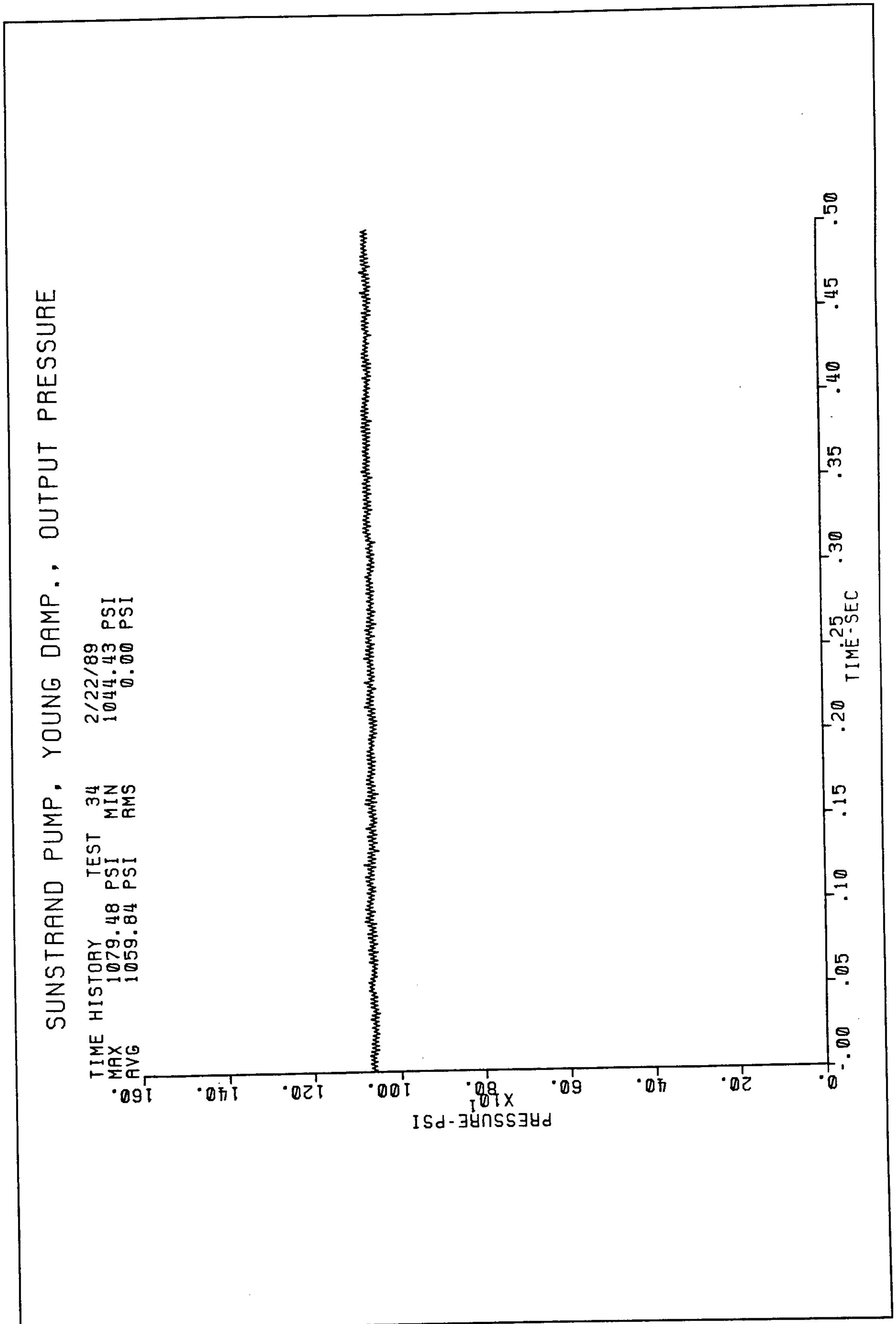
SUNSTRAND PUMP, NO DAMPENER, OUTPUT PRESSURE
TIME HISTORY TEST 36 2/24/89
MAX 1061.41 PSI MIN 1020.27 PSI
AVG 1040.45 PSI RMS 0.00 PSI
PRESSURE-PSI
X10^1
160. 140. 120. 100. 80. 60. 40. 20. 0.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


SUNSTRAND PUMP, NO DAMPENER, INPUT PRESSURE
TIME HISTORY TEST 36 2/24/89
MAX 29.86 PSI MIN 15.18 PSI
AVG 22.69 PSI RMS 2.24 PSI
PRESSURE-PSI
TIME-SEC

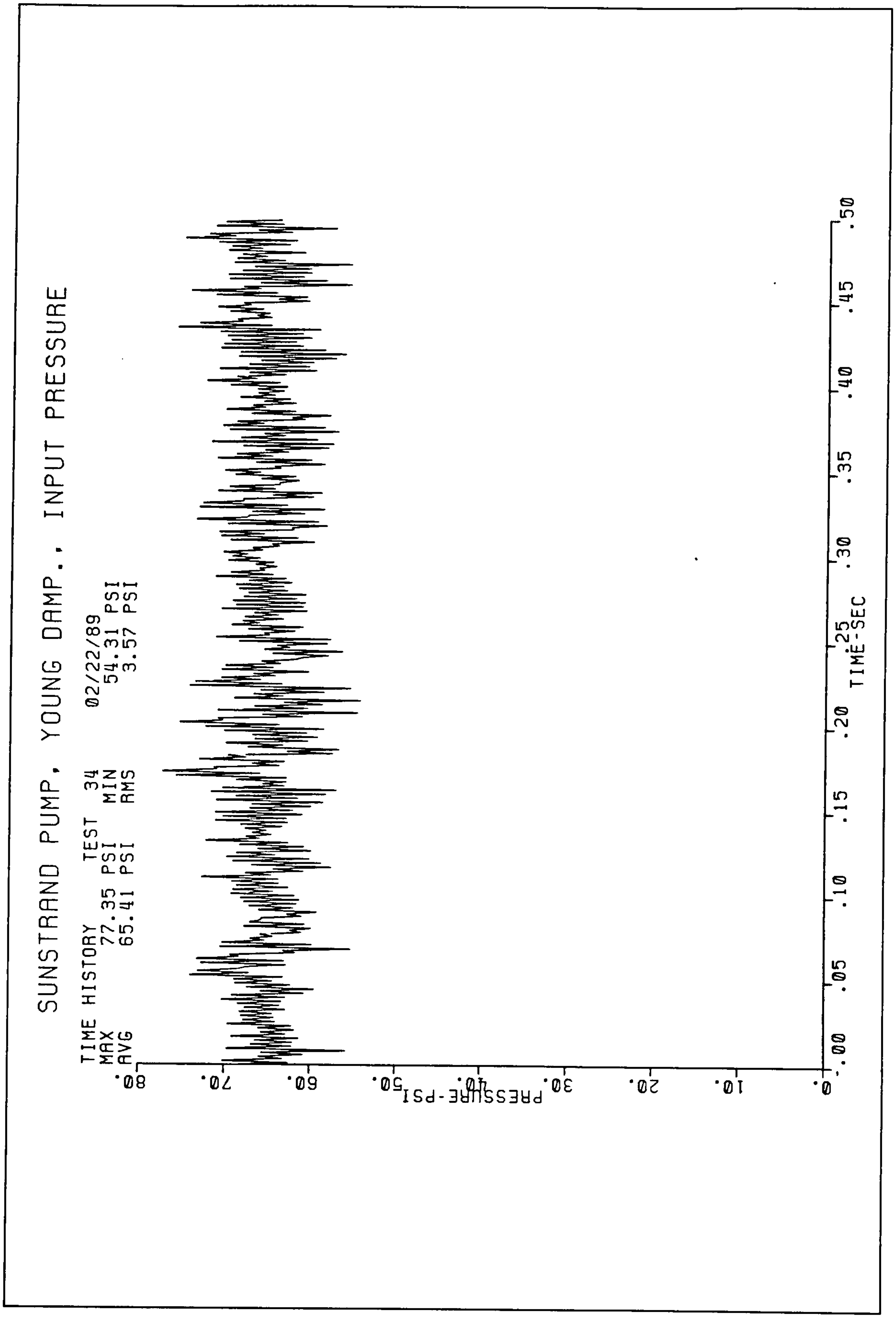

SUNSTRAND PUMP, NO DAMPENER, H. ACCEL. FL.
TIME HISTORY TEST 36 02/24/89
MAX 0.31 G'S MIN -0.41 G'S
AVG -0.01 G'S RMS 0.09 G'S
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
TIME-SEC
-.80 -.60 -.40 -.20 .00 .20 .40 .60 .80
ACCELERATION-G'S

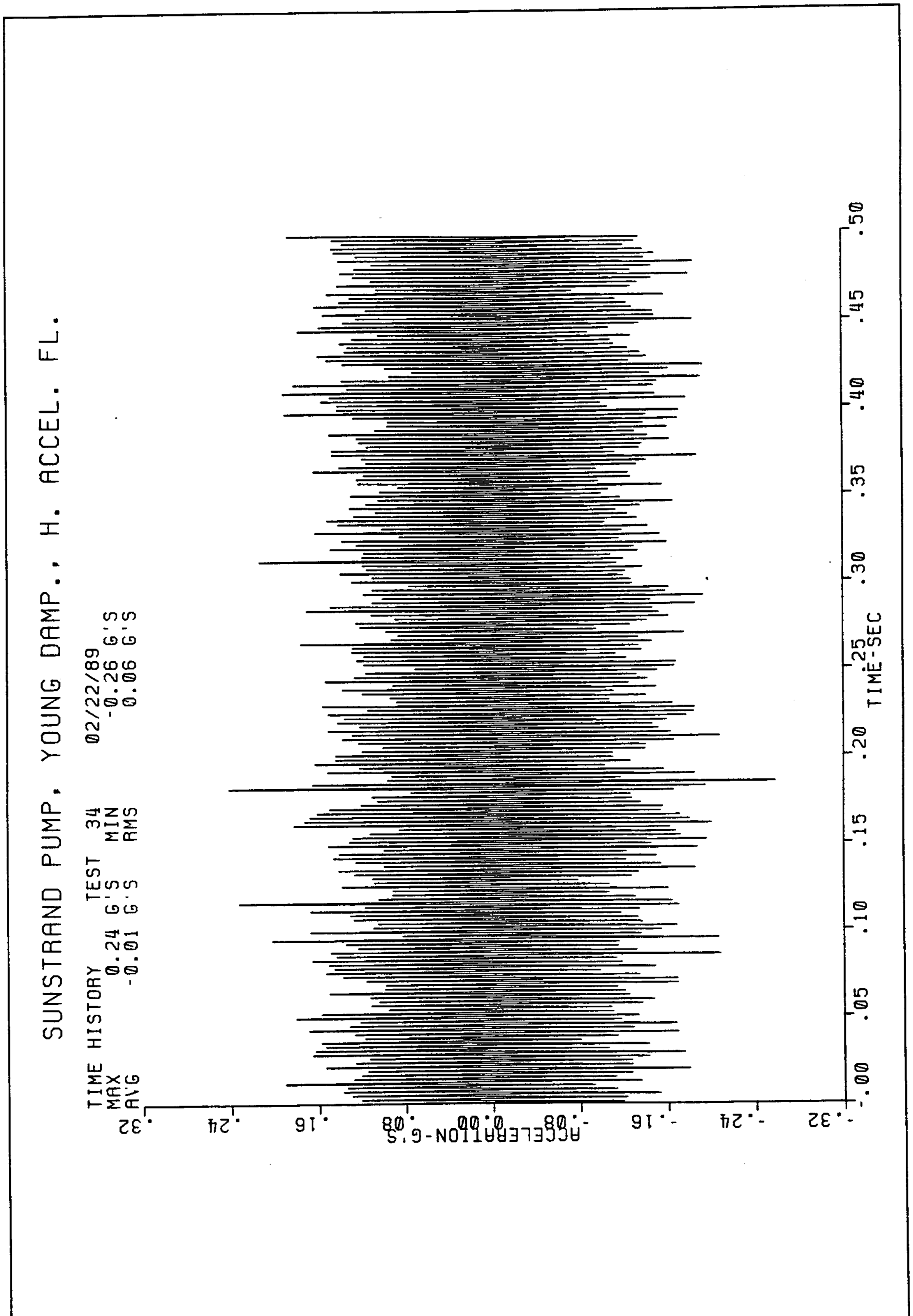

SUNSTRAND PUMP, NO DAMPENER, V. ACCEL. FL.
TIME HISTORY TEST 36 02/24/89
MAX 0.69 G'S MIN -0.60 G'S
AVG 0.00 G'S RMS 0.17 G'S
TIME-SEC
ACCELERATION-G'S
-.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
.80 .60 .40 .20 .00 -.20 -.40 -.60 -.80

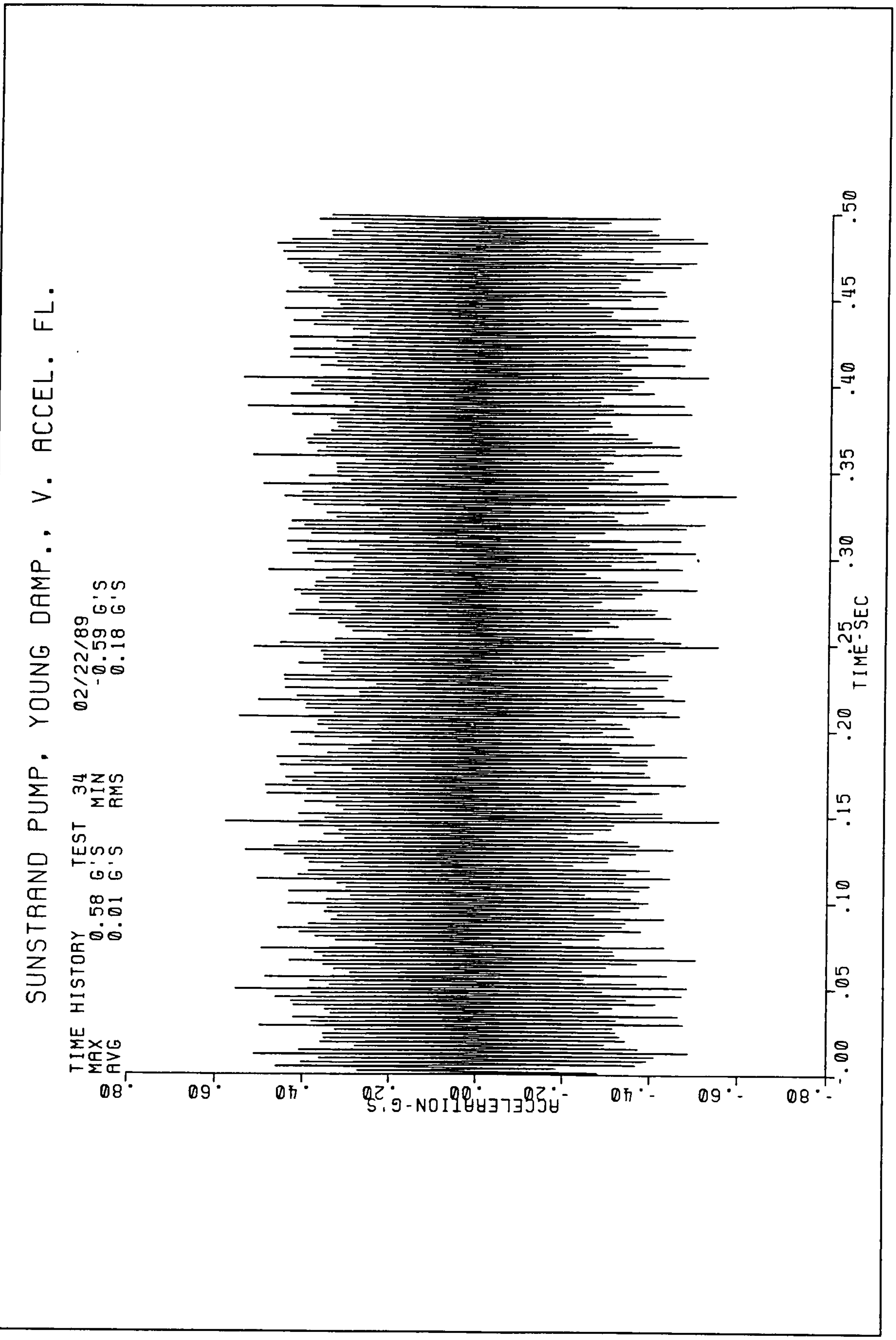
Young Engineering Pulsation Dampener



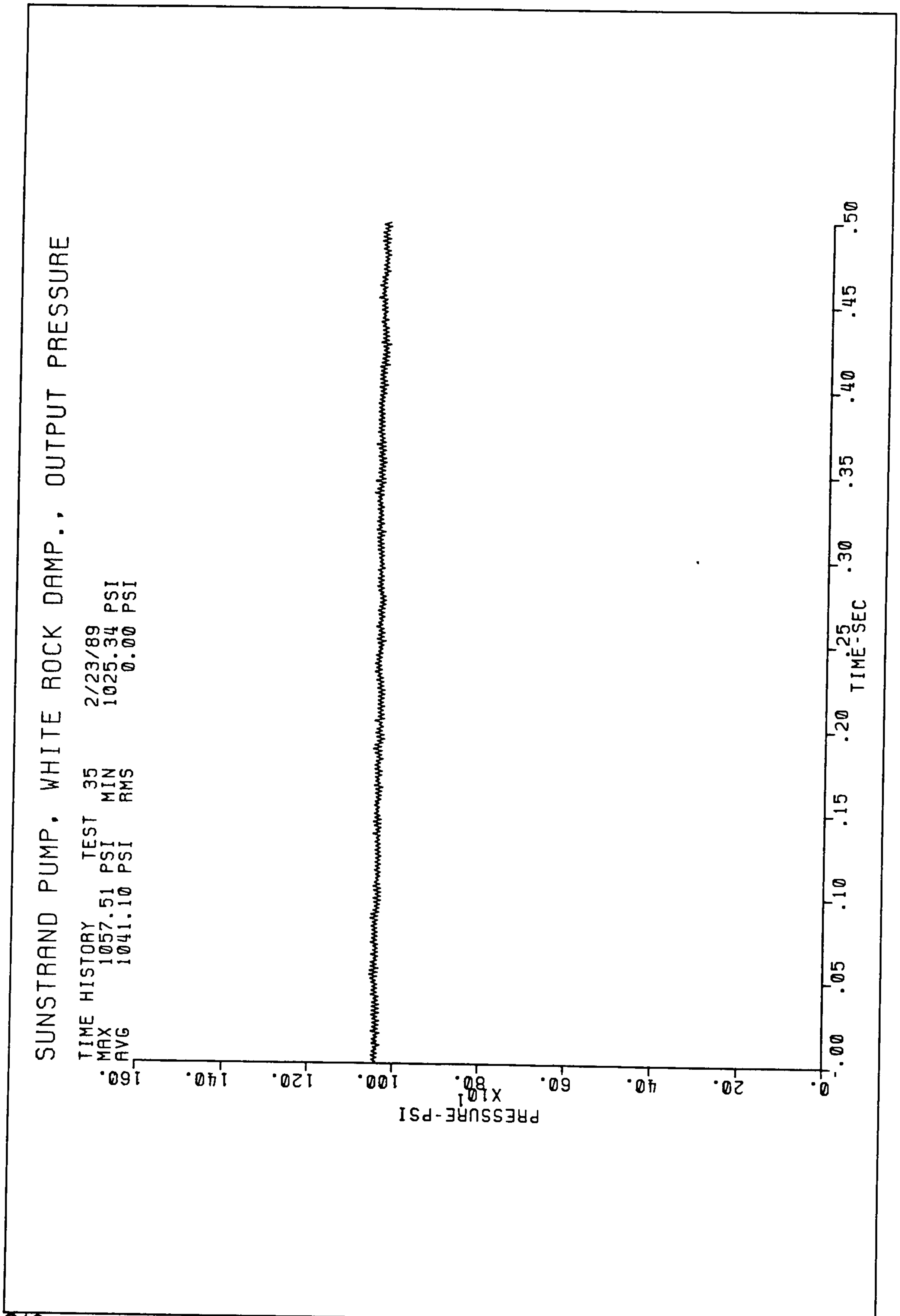
SUNSTRAND PUMP, YOUNG DAMP., OUTPUT PRESSURE
TIME HISTORY TEST 34 2/22/89
MAX 1079.48 PSI MIN 1044.43 PSI
AVG 1059.84 PSI RMS 0.00 PSI
PRESSURE-PSI
X10^1
0. 20. 40. 60. 80. 100. 120. 140. 160.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

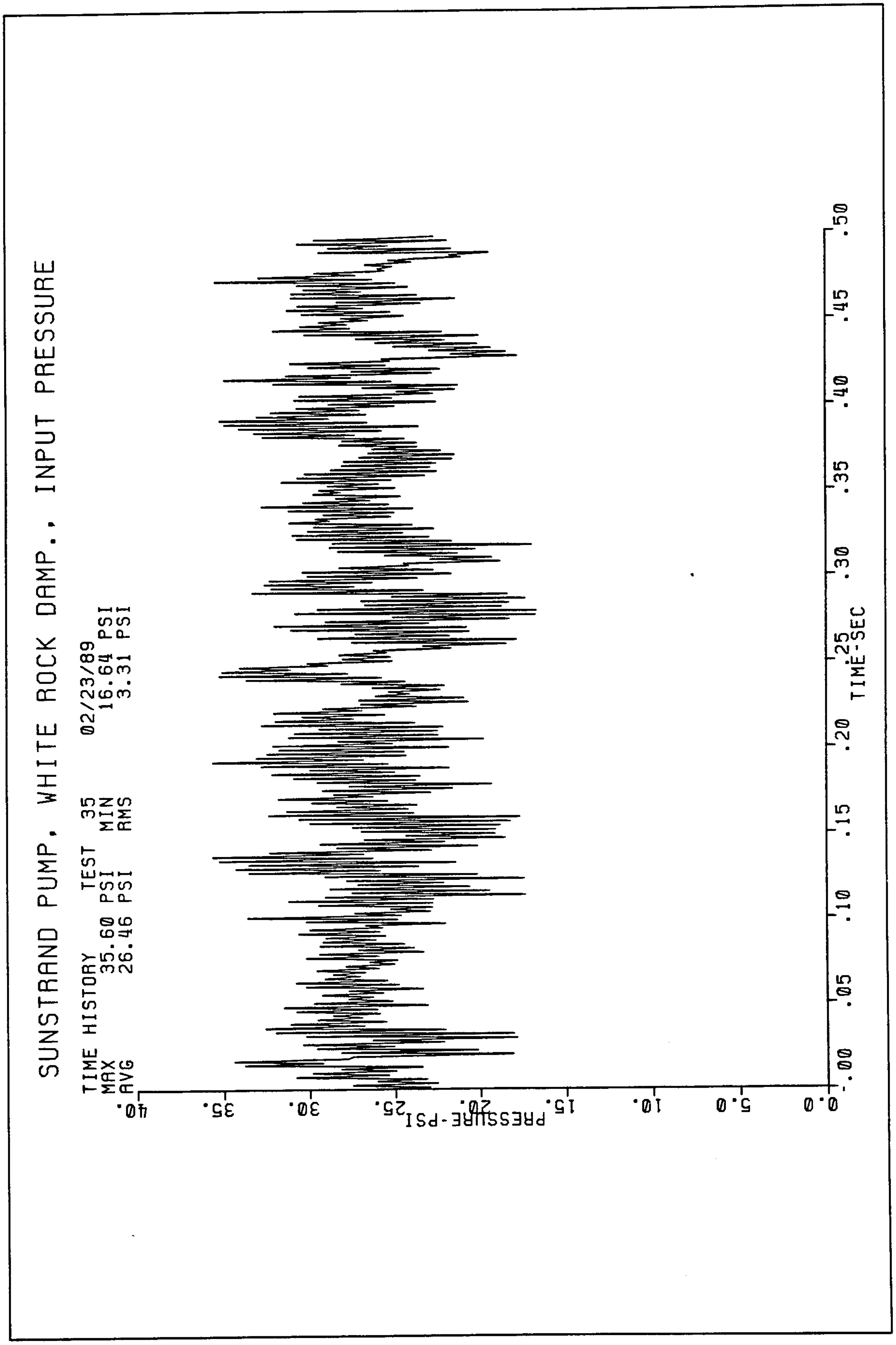

SUNSTRAND PUMP, YOUNG DAMP., INPUT PRESSURE
TIME HISTORY TEST 34 02/22/89
MAX 77.35 PSI MIN 54.31 PSI
AVG 65.41 PSI RMS 3.57 PSI
PRESSURE-PSI
0. 10. 20. 30. 40. 50. 60. 70. 80.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

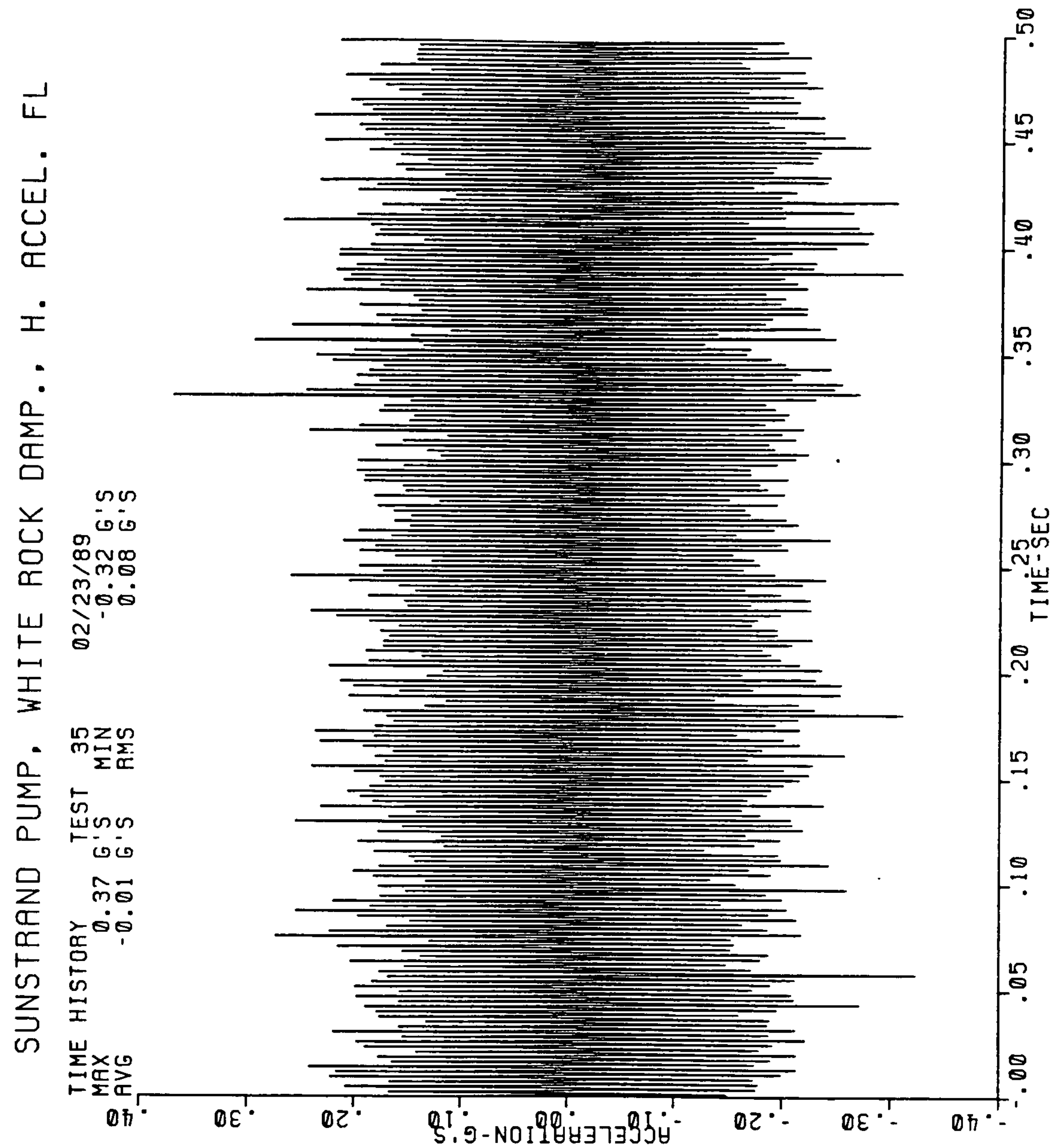

SUNSTRAND PUMP, YOUNG DAMP., H. ACCEL. FL.
TIME HISTORY TEST 34 02/22/89
MAX 0.24 G'S MIN -0.26 G'S
AVG -0.01 G'S RMS 0.06 G'S
ACCELERATION-G'S
.32
.24
.16
.08
0.00
-.08
-.16
-.24
-.32
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50


SUNSTRAND PUMP, YOUNG DAMP., V. ACCEL. FL.
TIME HISTORY TEST 34 02/22/89
MAX 0.58 G'S MIN -0.59 G'S
AVG 0.01 G'S RMS 0.18 G'S
.80 .60 .40 .20 .00 -.20 -.40 -.60 -.80
ACCELERATION-G'S
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
TIME-SEC

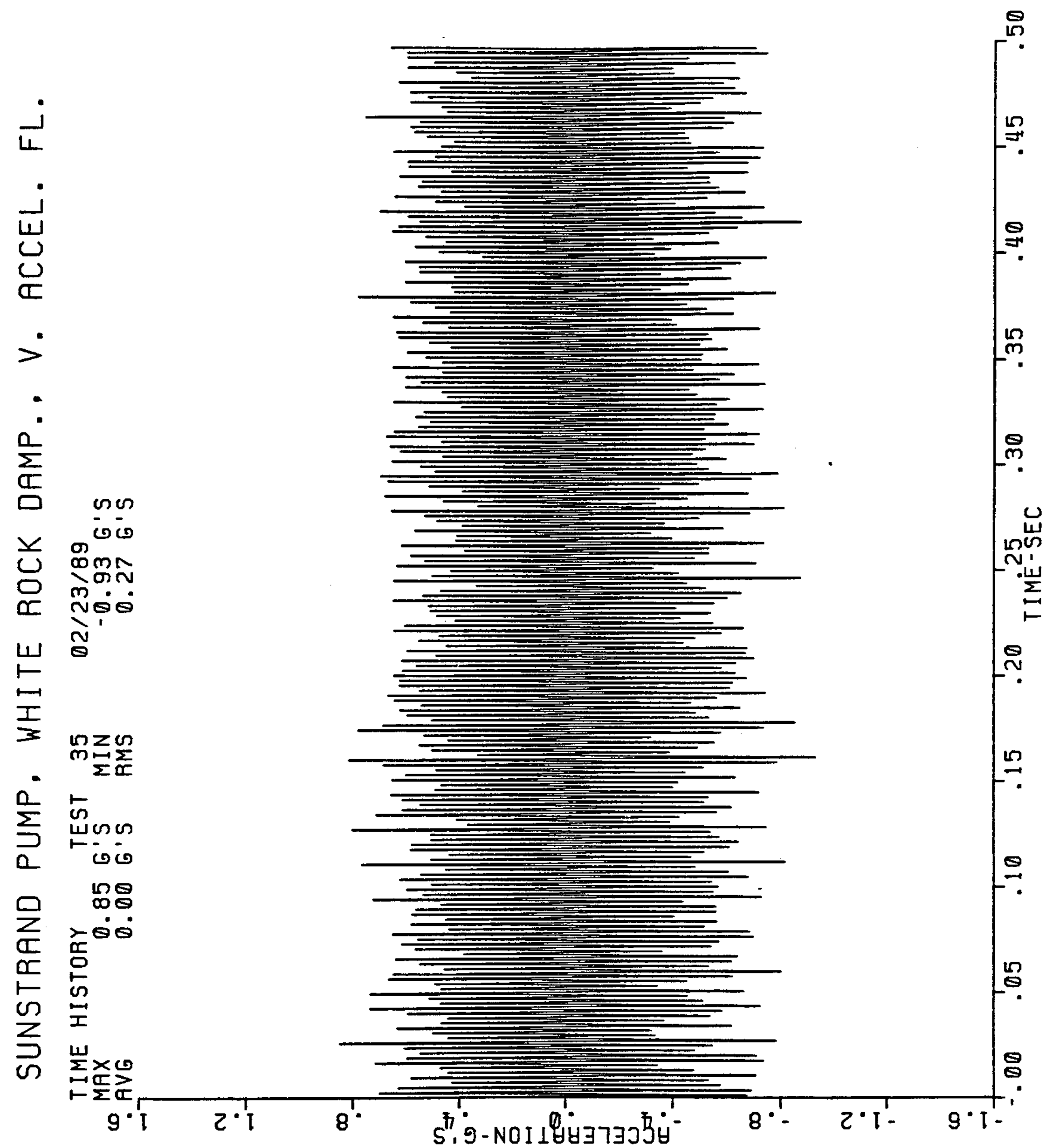
White Rock Pulsation Dampener


SUNSTRAND PUMP, WHITE ROCK DAMP., OUTPUT PRESSURE
TIME HISTORY TEST 35 2/23/89
MAX 1057.51 PSI MIN 1025.34 PSI
AVG 1041.10 PSI RMS 0.00 PSI
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
PRESSURE-PSI
X10^1
0. 20. 40. 60. 80. 100. 120. 140. 160.

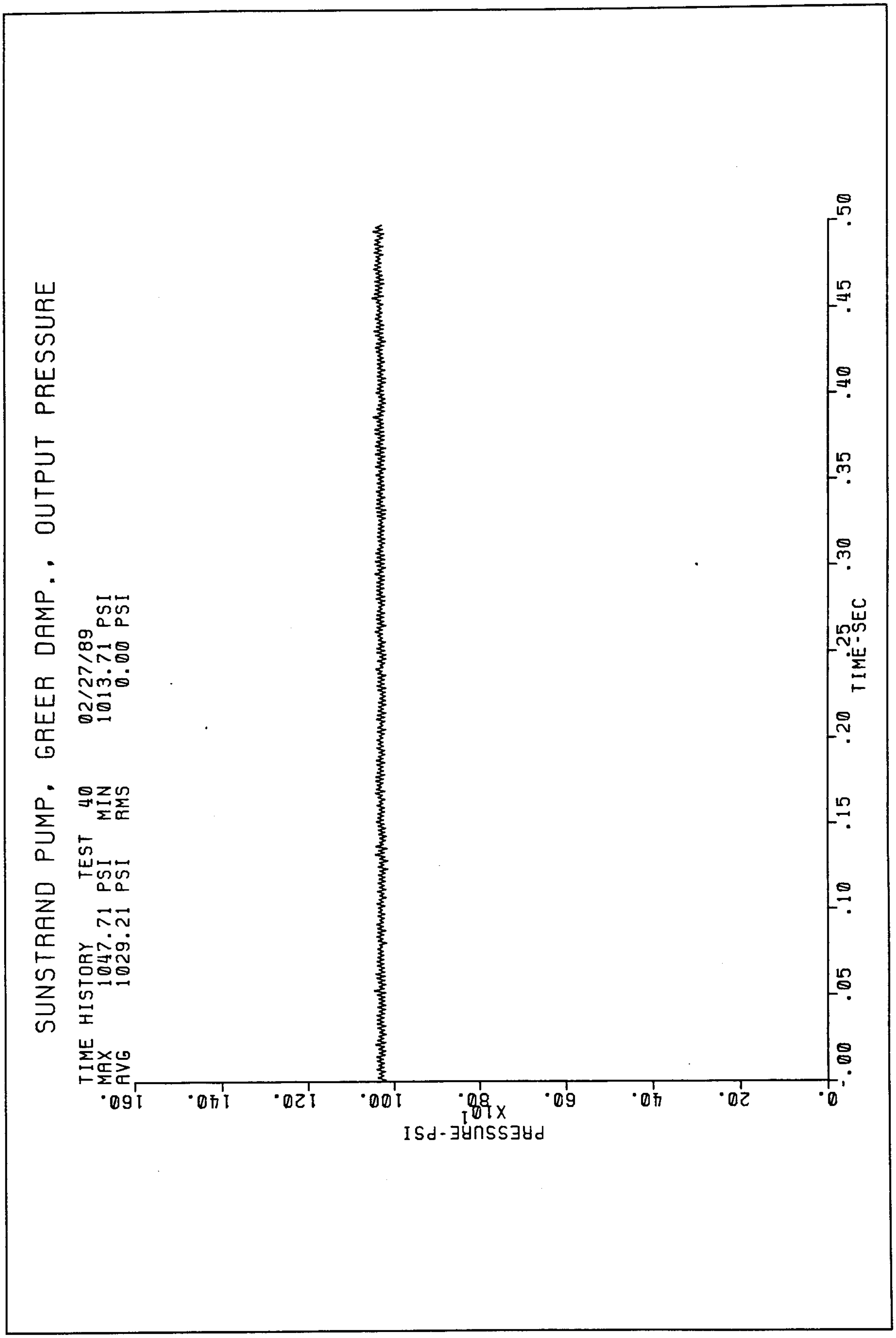

SUNSTRAND PUMP, WHITE ROCK DAMP., INPUT PRESSURE
TIME HISTORY TEST 35 02/23/89
MAX 35.60 PSI MIN 16.64 PSI
AVG 26.46 PSI RMS 3.31 PSI
PRESSURE-PSI
0.0 5.0 10. 15. 20. 25. 30. 35. 40.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

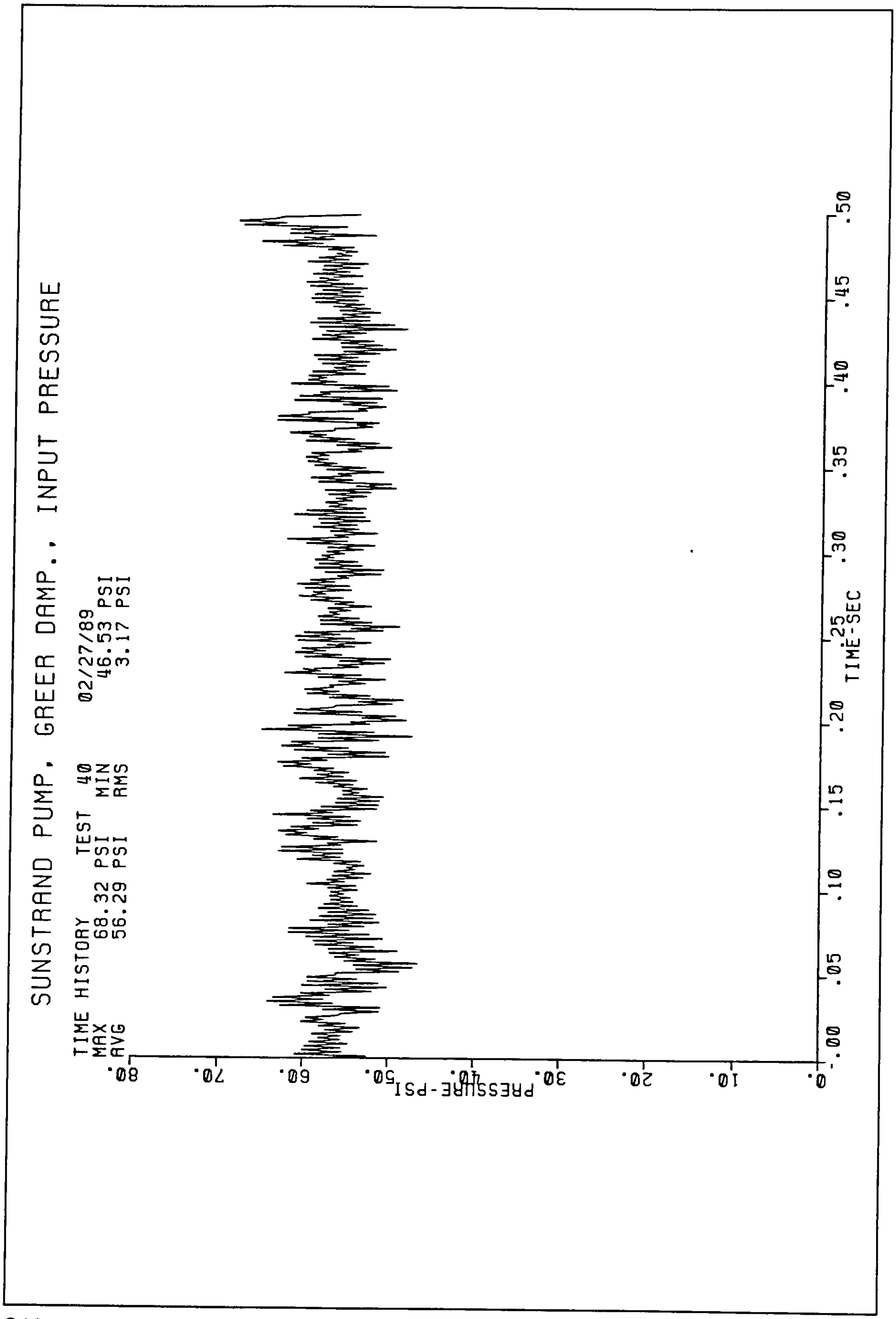


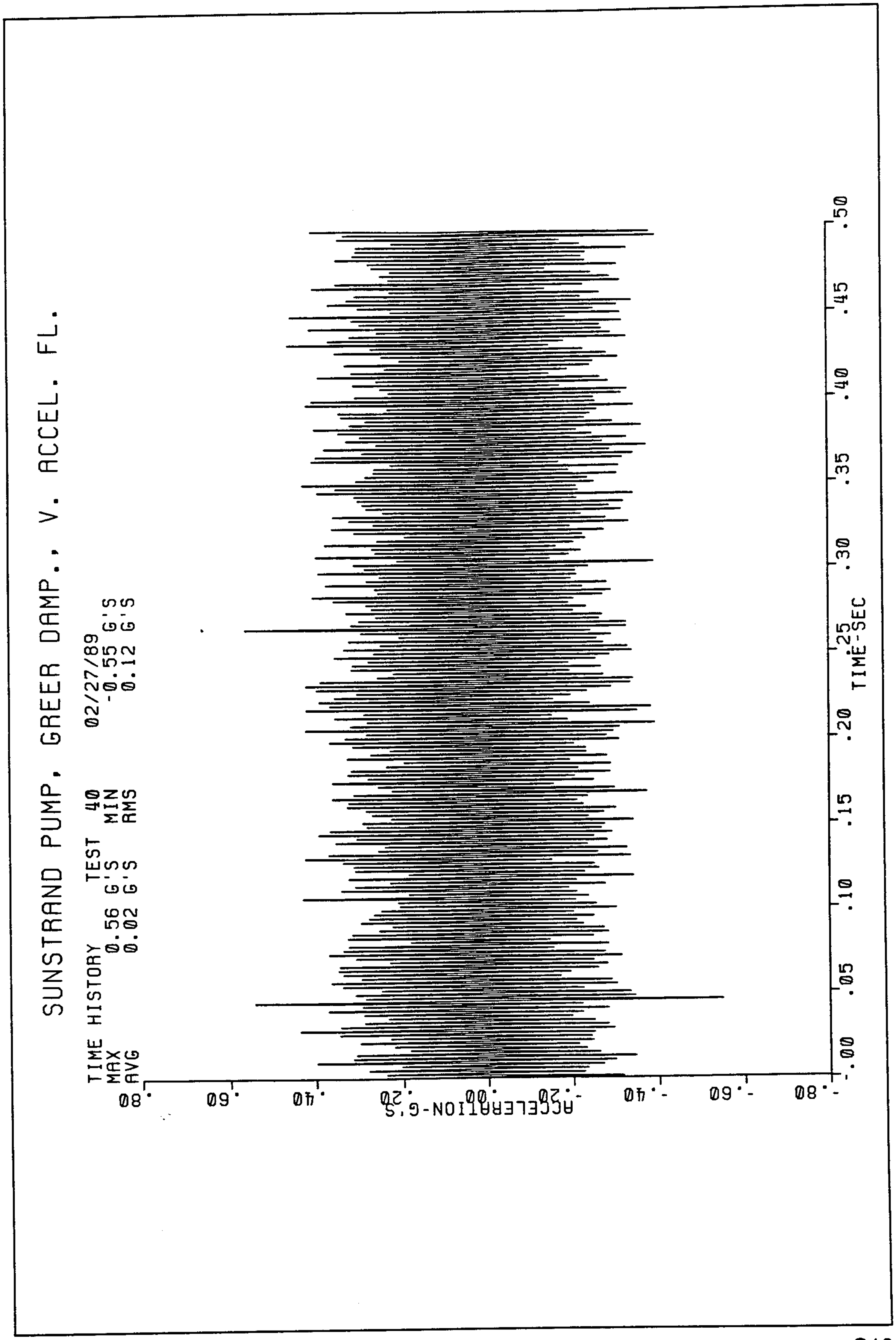
SUNSTRAND PUMP, WHITE ROCK DAMP., H. ACCEL. FL
TIME HISTORY TEST 35 02/23/89
MAX 0.37 G'S MIN -0.32 G'S
AVG -0.01 G'S RMS 0.08 G'S
TIME-SEC
ACCELERATION-G'S
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.40
.30
.20
.10
.00
-.10
-.20
-.30
-.40


SUNSTRAND PUMP, WHITE ROCK DAMP., V. ACCEL. FL.
TIME HISTORY TEST 35 02/23/89
MAX 0.85 G'S MIN -0.93 G'S
AVG 0.00 G'S RMS 0.27 G'S
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
ACCELERATION-G'S
1.6 1.2 .8 .4 0 -.4 -.8 -1.2 -1.6

Greer 1-Gal (4-Qt) Pulsation Dampener

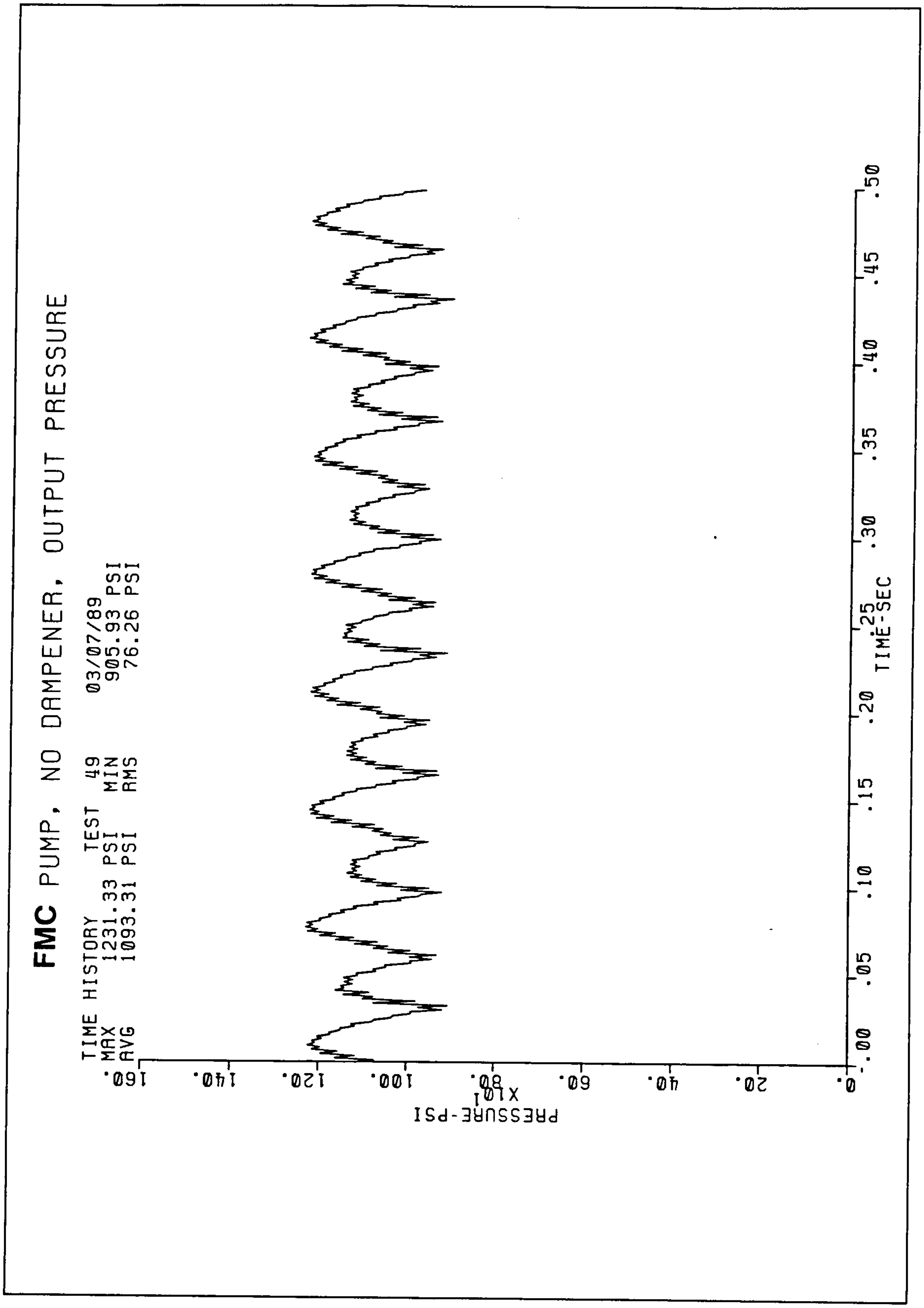

SUNSTRAND PUMP, GREER DAMP., OUTPUT PRESSURE
TIME HISTORY TEST 40 02/27/89
MAX 1047.71 PSI MIN 1013.71 PSI
AVG 1029.21 PSI RMS 0.00 PSI
PRESSURE-PSI
X10^1
0.
20.
40.
60.
80.
100.
120.
140.
160.
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50


SUNSTRAND PUMP, GREER DAMP.., INPUT PRESSURE
TIME HISTORY TEST 40 02/27/89
MAX 68.32 PSI MIN 46.53 PSI
AVG 56.29 PSI RMS 3.17 PSI
PRESSURE-PSI
TIME-SEC

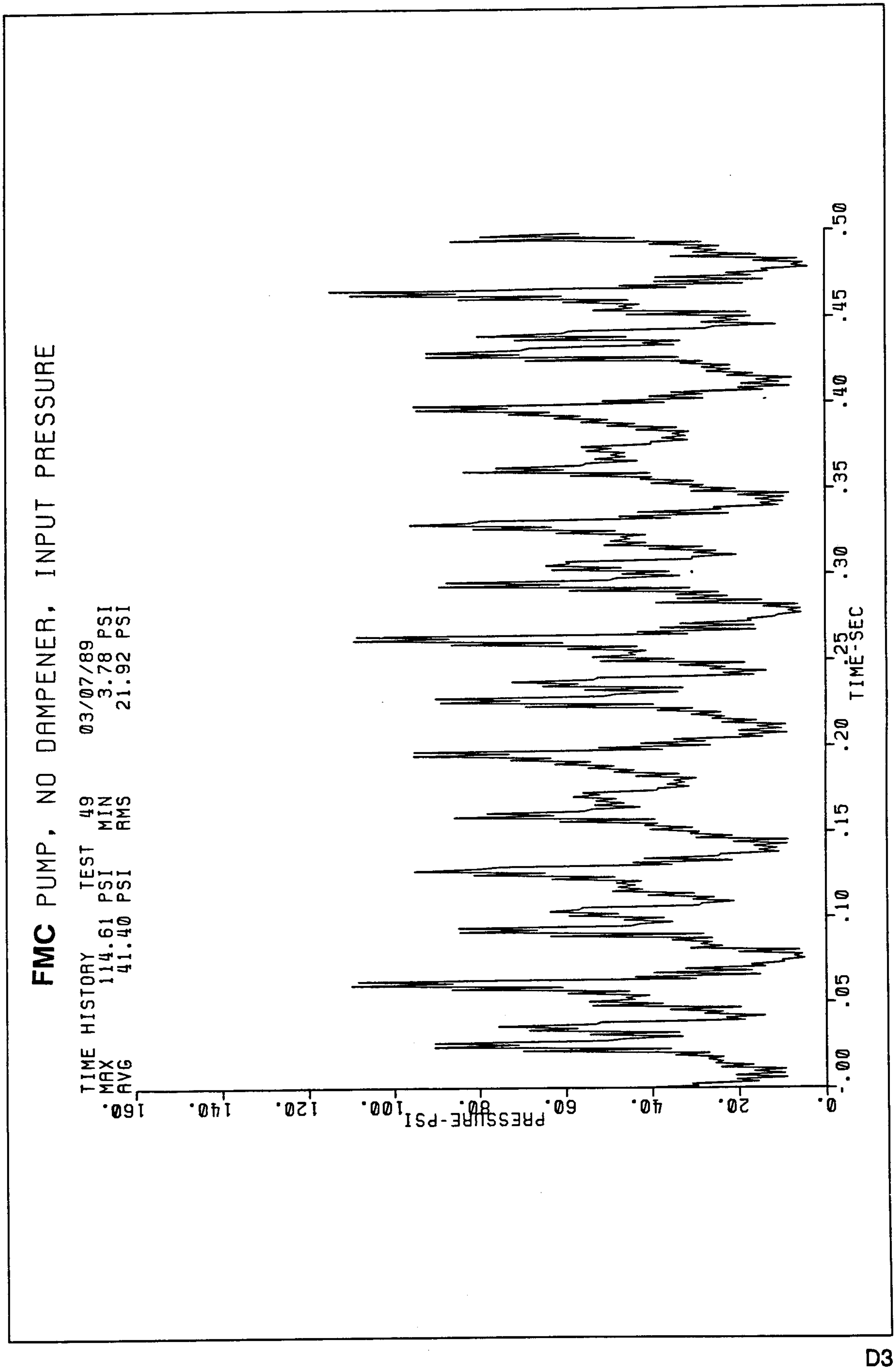

SUNSTRAND PUMP, GREER DAMP., V. ACCEL. FL.
TIME HISTORY TEST 40 02/27/89
MAX 0.56 G'S MIN -0.55 G'S
AVG 0.02 G'S RMS 0.12 G'S
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
TIME-SEC
.80 .60 .40 .20 .00 -.20 -.40 -.60 -.80
ACCELERATION-G'S

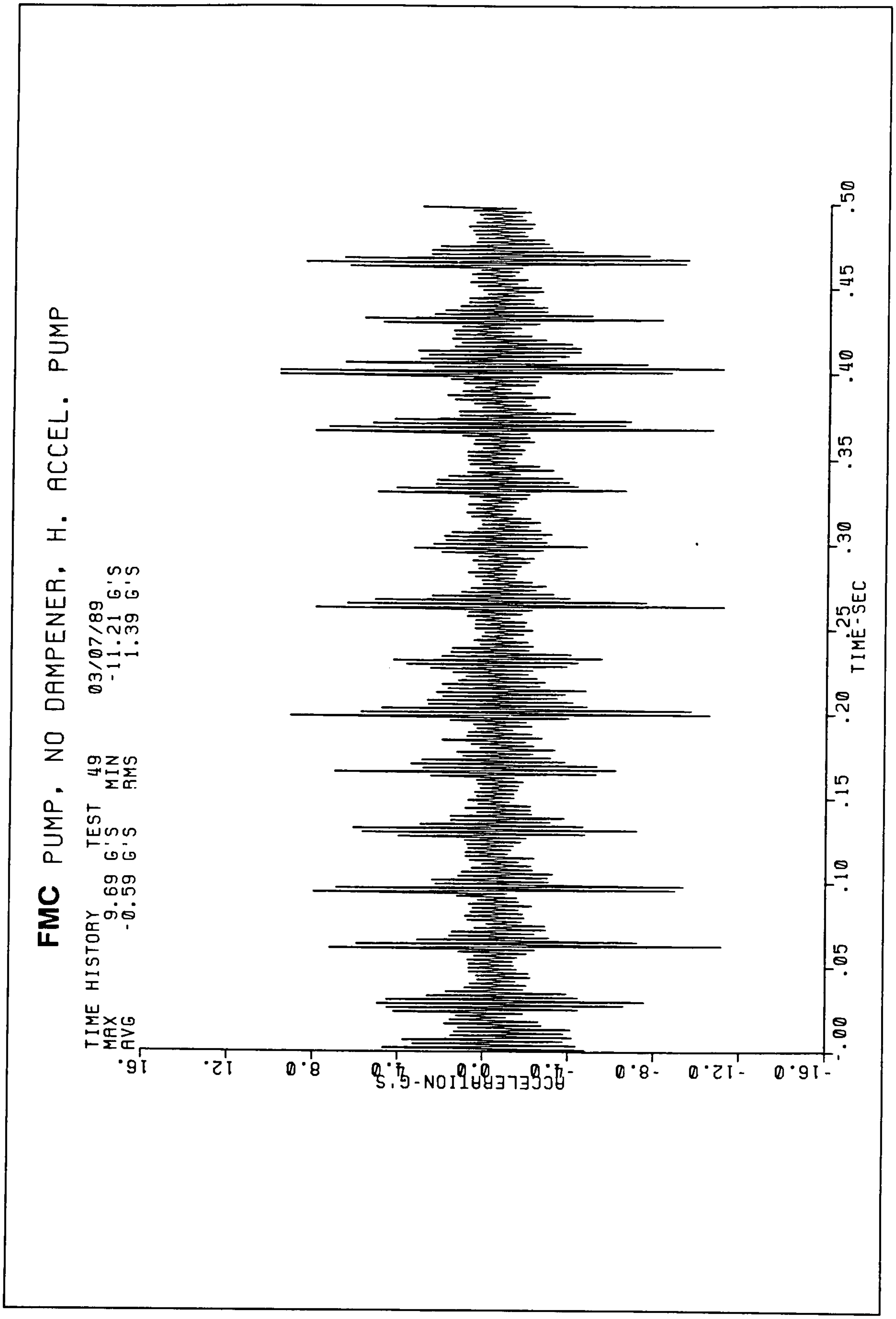
Appendix D
FMC Pump

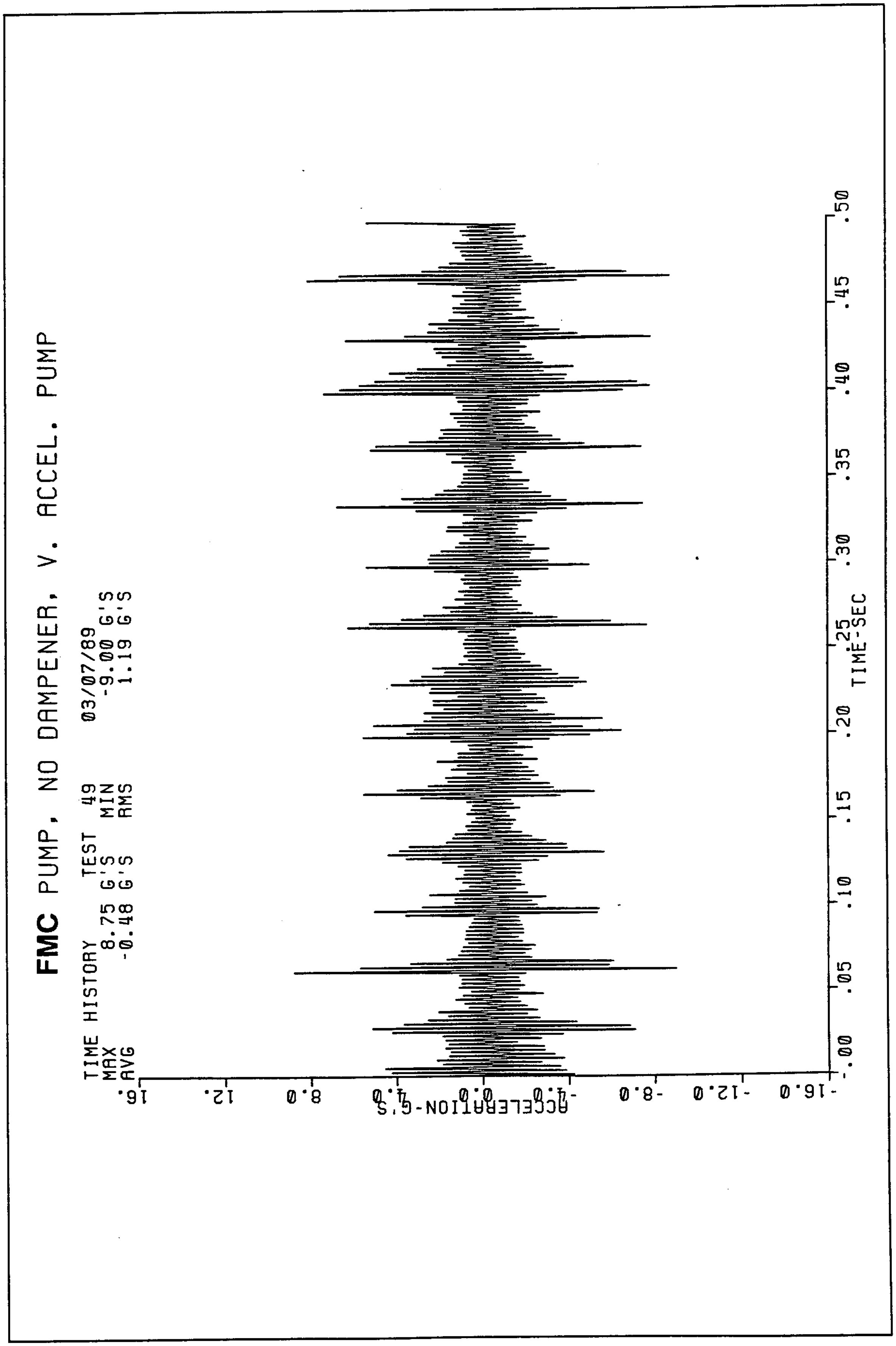
No Pulsation Dampener



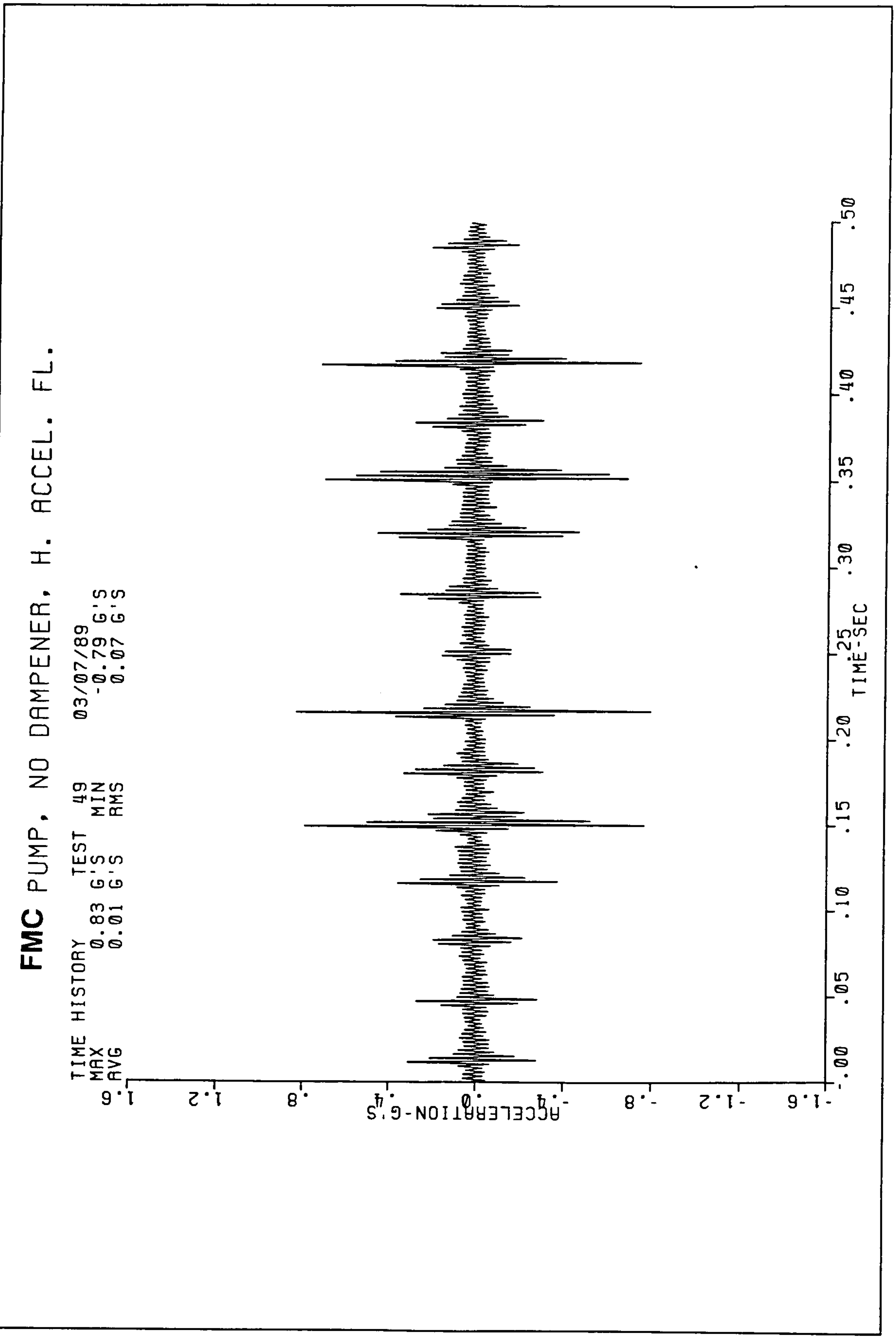
FMC PUMP, NO DAMPENER, OUTPUT PRESSURE
TIME HISTORY TEST 49 03/07/89
MAX 1231.33 PSI MIN 905.93 PSI
AVG 1093.31 PSI RMS 76.26 PSI
PRESSURE-PSI
X10^1
0. 20. 40. 60. 80. 100. 120. 140. 160.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

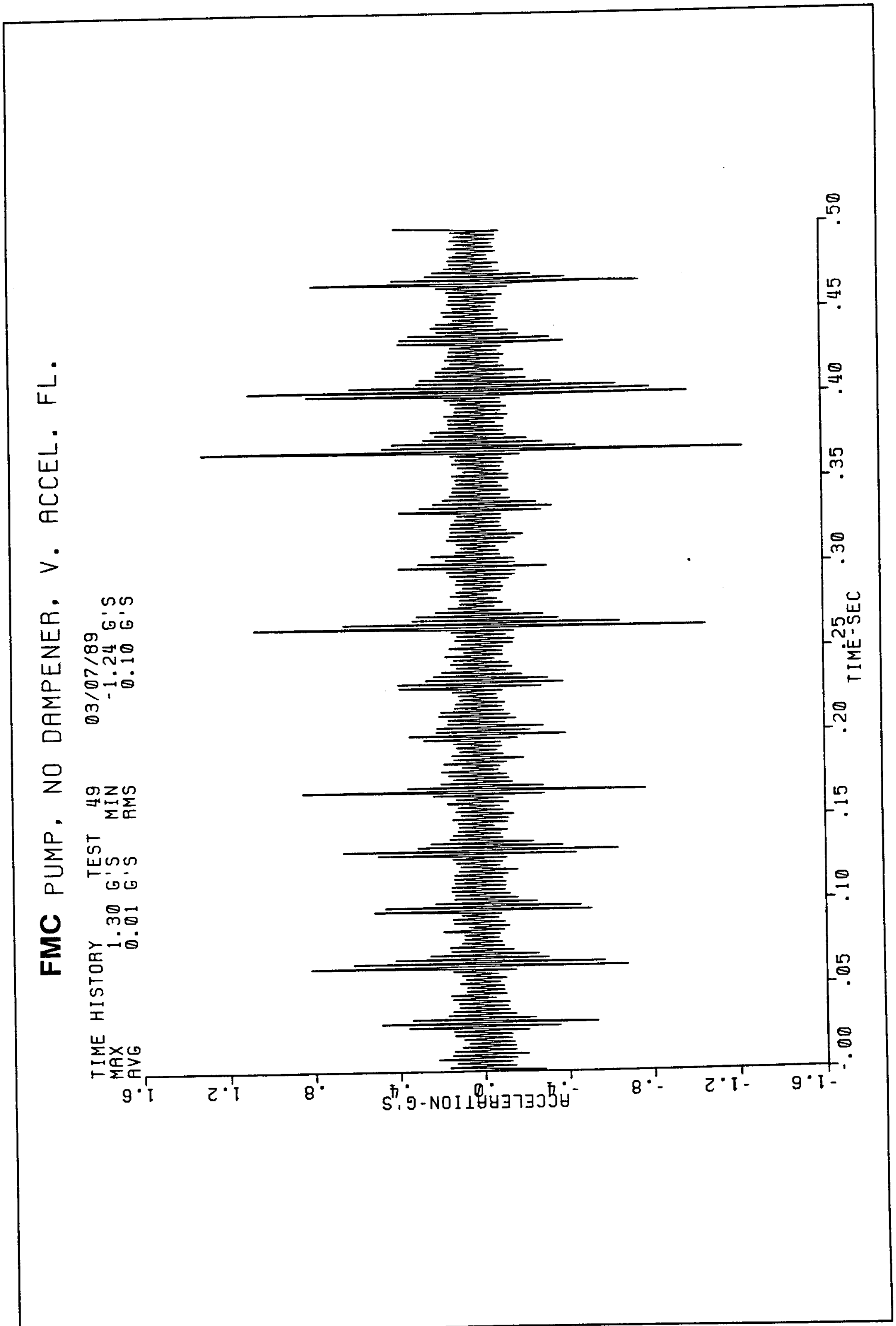

FMC PUMP, NO DAMPENER, INPUT PRESSURE
TIME HISTORY TEST 49 03/07/89
MAX 114.61 PSI MIN 3.78 PSI
AVG 41.40 PSI RMS 21.92 PSI
PRESSURE-PSI
0. 20. 40. 60. 80. 100. 120. 140. 160.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


FMC PUMP, NO DAMPENER, H. ACCEL. PUMP
TIME HISTORY TEST 49 03/07/89
MAX 9.69 G'S MIN -11.21 G'S
AVG -0.59 G'S RMS 1.39 G'S
TIME-SEC
ACCELERATION-G'S

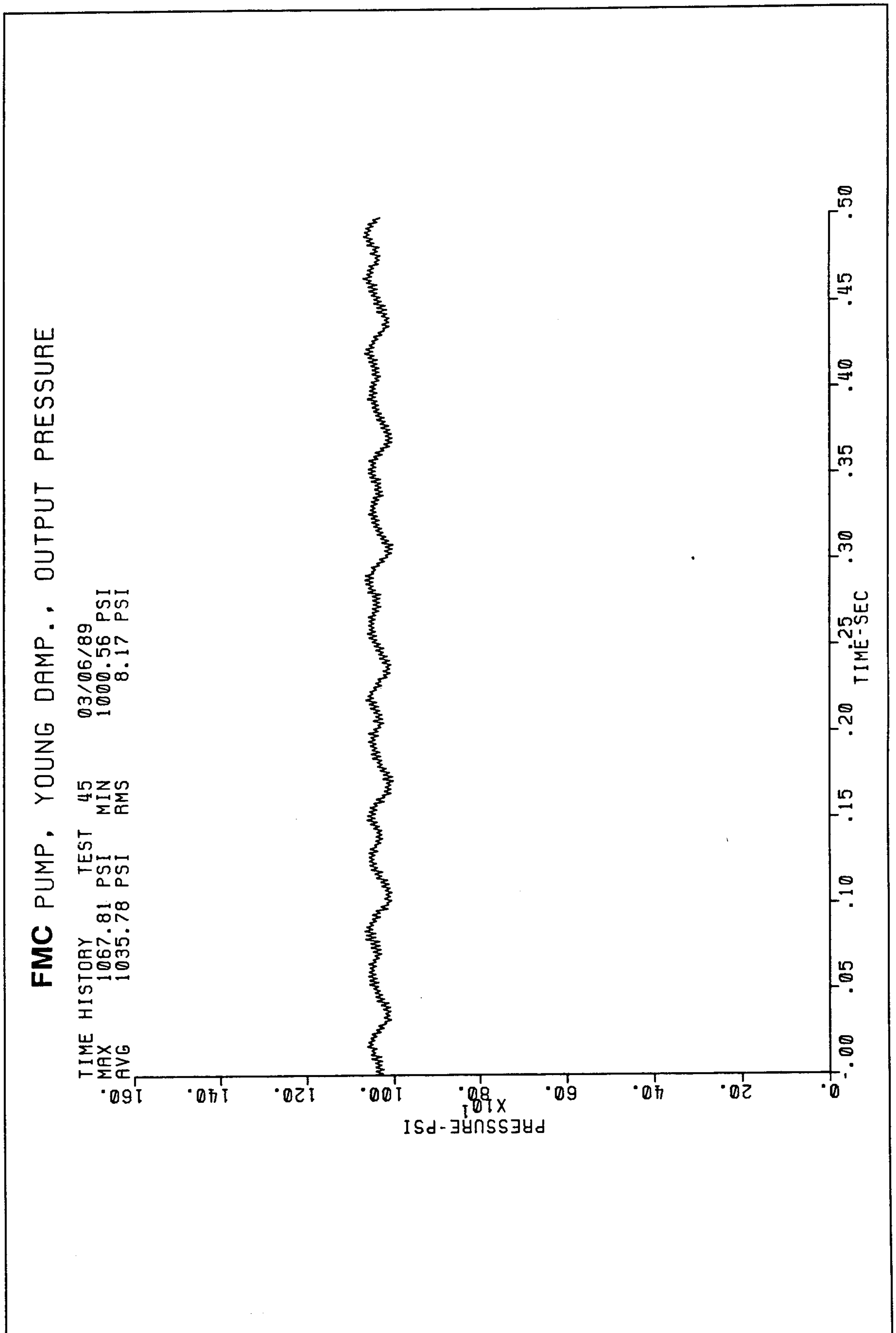


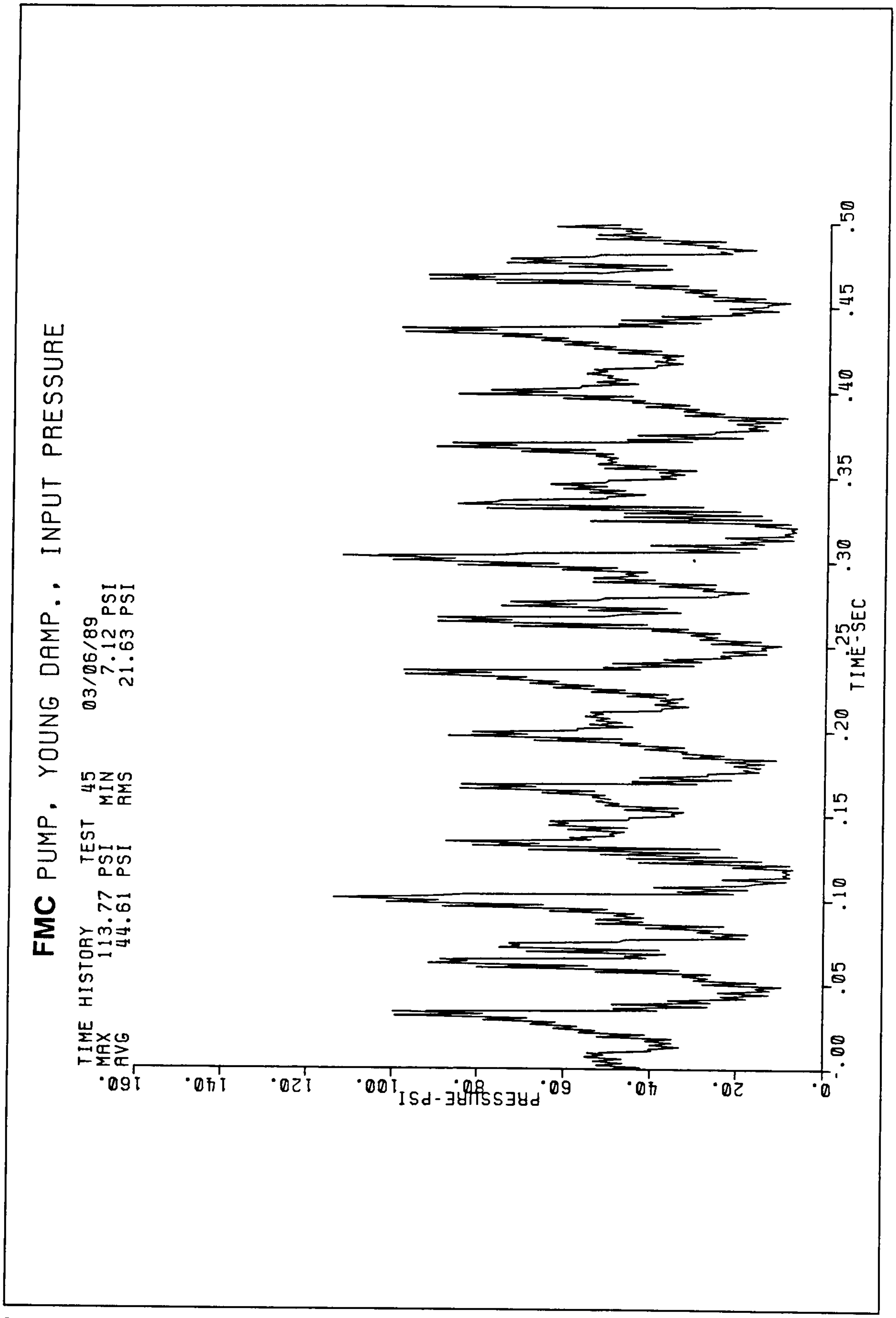
FMC PUMP, NO DAMPENER, V. ACCEL. PUMP
TIME HISTORY TEST 49 03/07/89
MAX 8.75 G'S MIN -9.00 G'S
AVG -0.48 G'S RMS 1.19 G'S
ACCELERATION-G'S
16. 12. 8.0 4.0 0.0 -4.0 -8.0 -12.0 -16.0
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

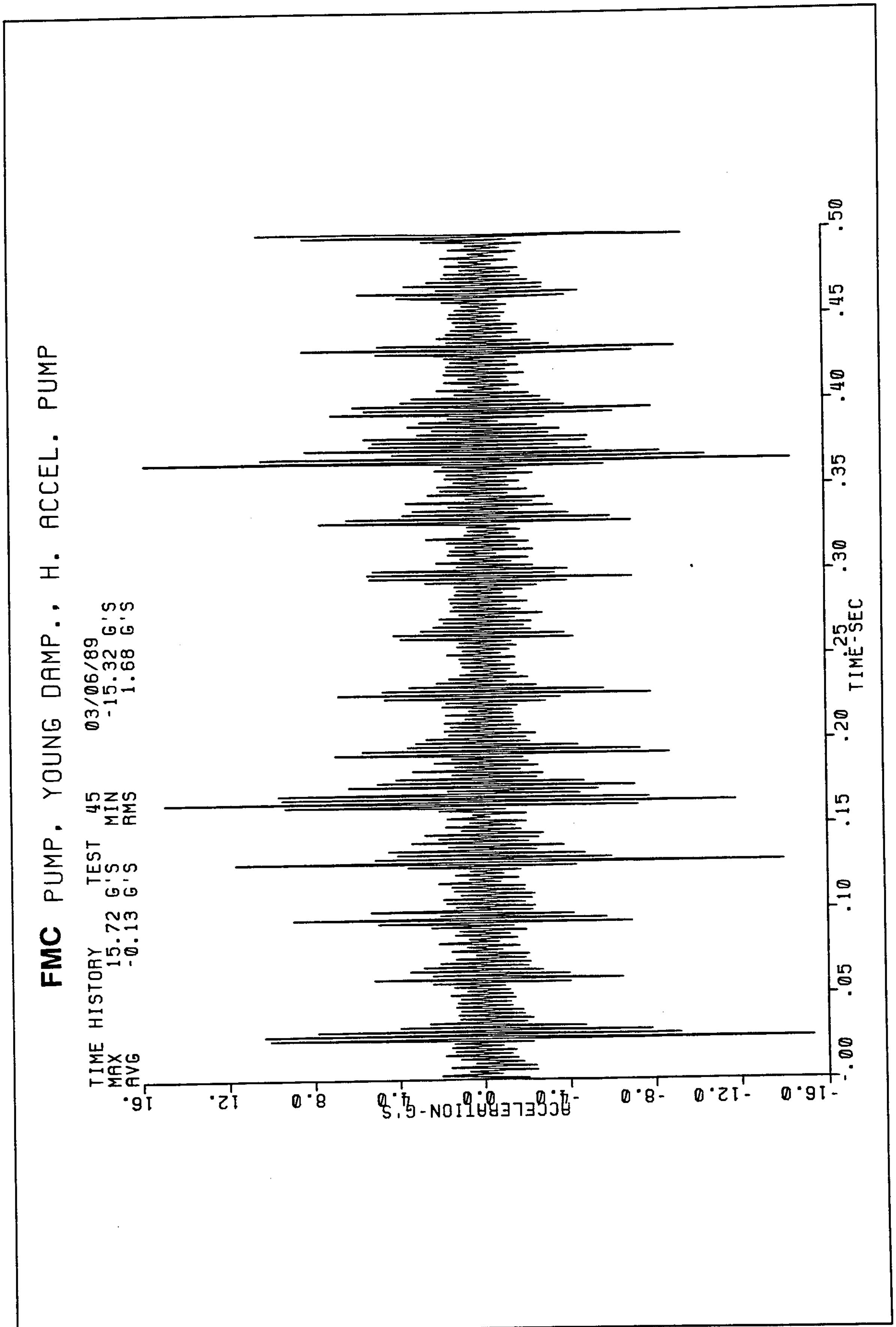

FMC PUMP, NO DAMPENER, H. ACCEL. FL.
TIME HISTORY TEST 49 03/07/89
MAX 0.83 G'S MIN -0.79 G'S
AVG 0.01 G'S RMS 0.07 G'S
ACCELERATION-G'S
1.6
1.2
.8
.4
0
-.4
-.8
-1.2
-1.6
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50

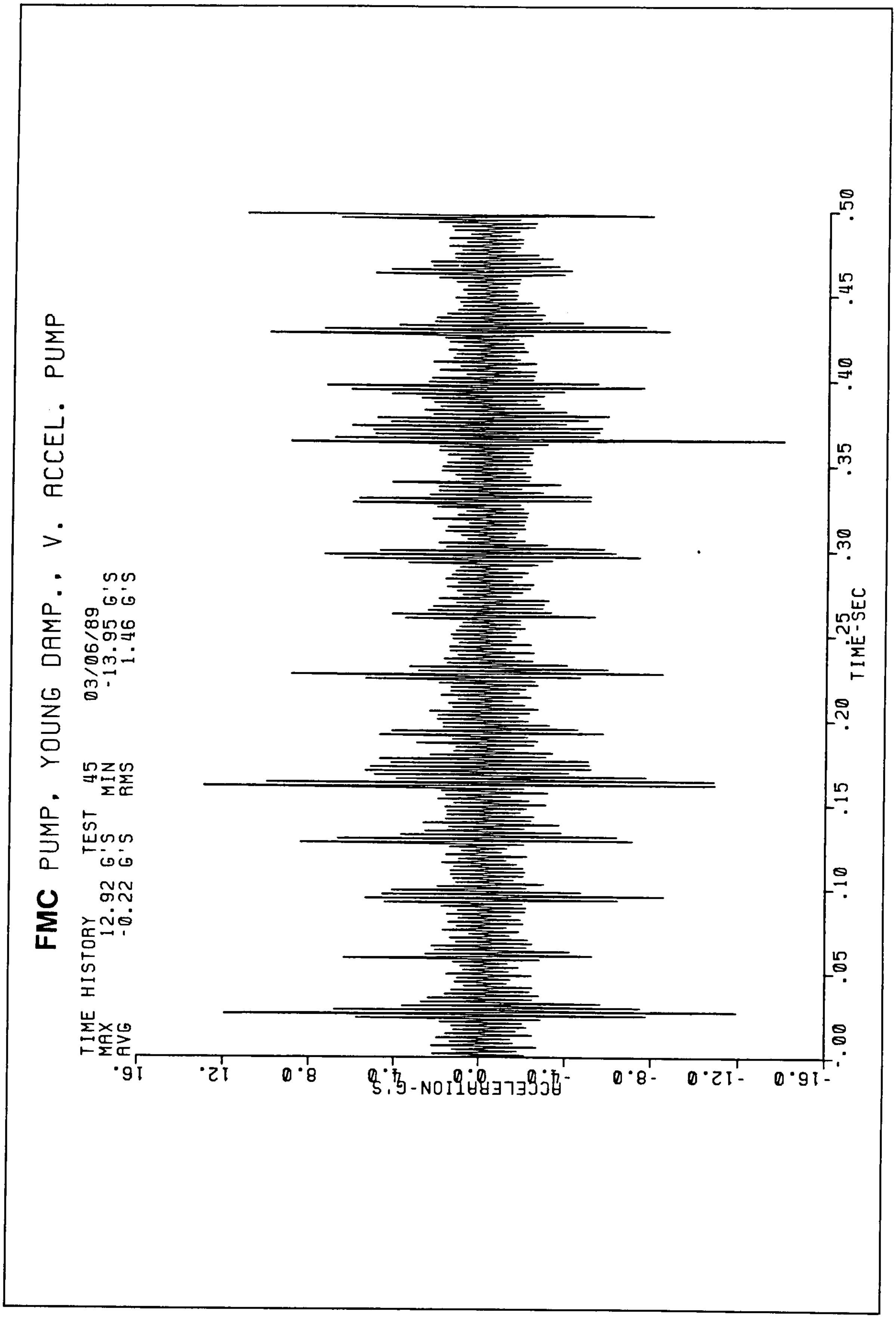

FMC PUMP, NO DAMPENER, V. ACCEL. FL.
TIME HISTORY TEST 49 03/07/89
MAX 1.30 G'S MIN -1.24 G'S
AVG 0.01 G'S RMS 0.10 G'S
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
ACCELERATION-G'S
1.6 1.2 .8 .4 0 -.4 -.8 -1.2 -1.6

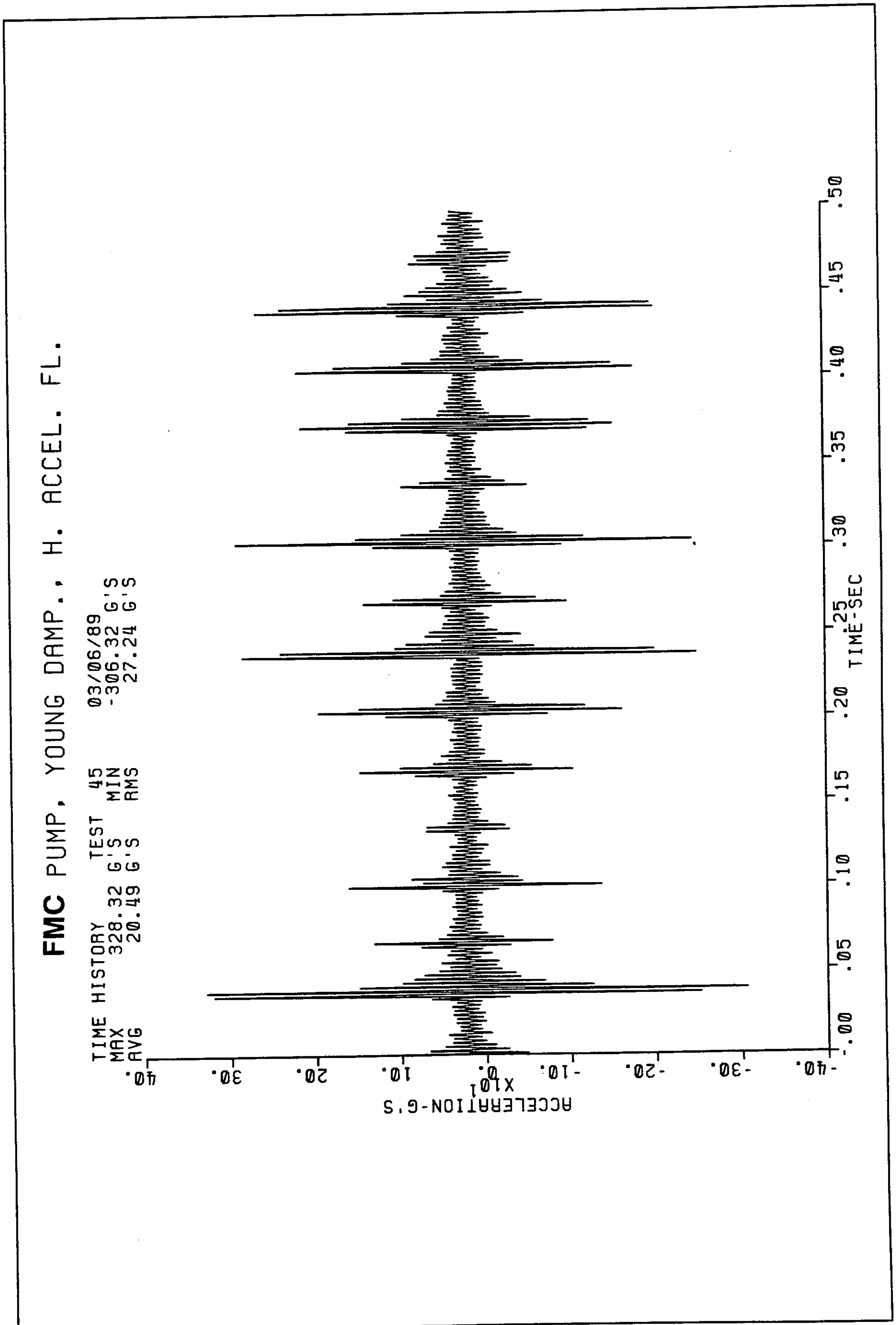
Young Engineering Pulsation Dampener

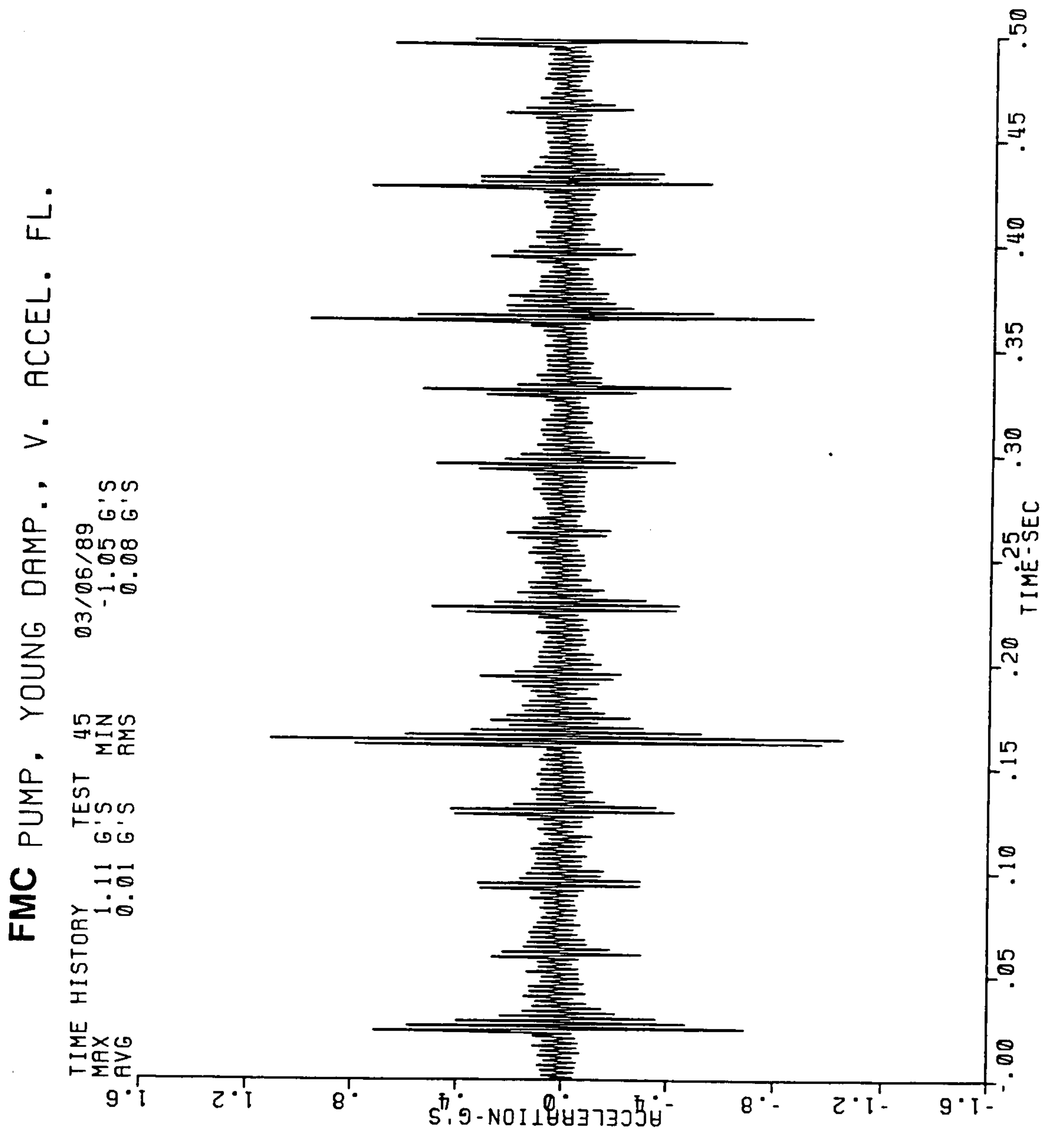

FMC PUMP, YOUNG DAMP., OUTPUT PRESSURE
TIME HISTORY TEST 45 03/06/89
MAX 1067.81 PSI MIN 1000.56 PSI
AVG 1035.78 PSI RMS 8.17 PSI
PRESSURE-PSI
X10^1
TIME-SEC
0. 20. 40. 60. 80. 100. 120. 140. 160.
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


FMC PUMP, YOUNG DAMP., INPUT PRESSURE
TIME HISTORY TEST 45 03/06/89
MAX 113.77 PSI MIN 7.12 PSI
AVG 44.61 PSI RMS 21.63 PSI
PRESSURE-PSI
TIME-SEC
0. 20. 40. 60. 80. 100. 120. 140. 160.
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

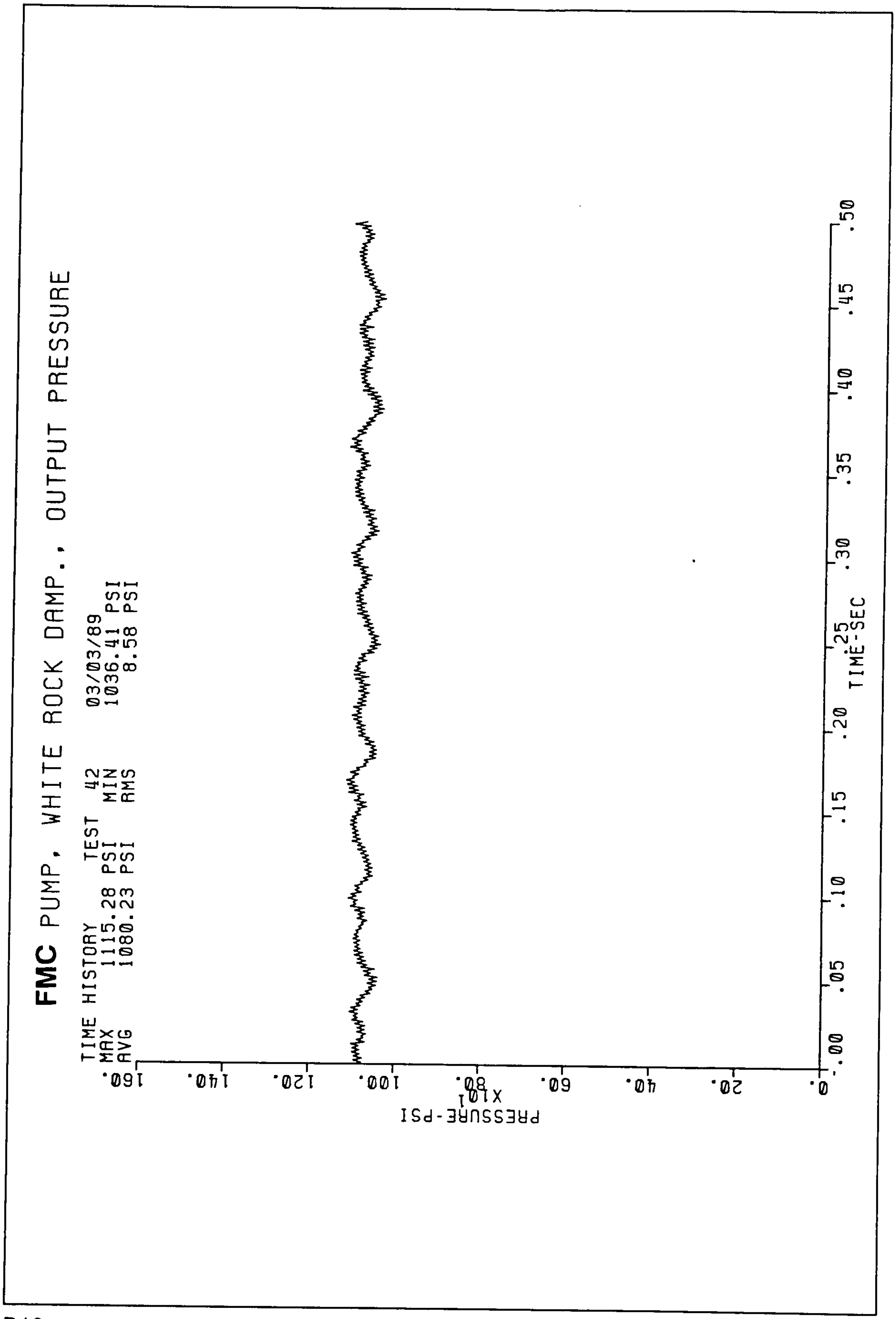

FMC PUMP, YOUNG DAMP., H. ACCEL. PUMP
TIME HISTORY TEST 45 03/06/89
MAX 15.72 G'S MIN -15.32 G'S
AVG -0.13 G'S RMS 1.68 G'S
TIME-SEC
ACCELERATION-G'S

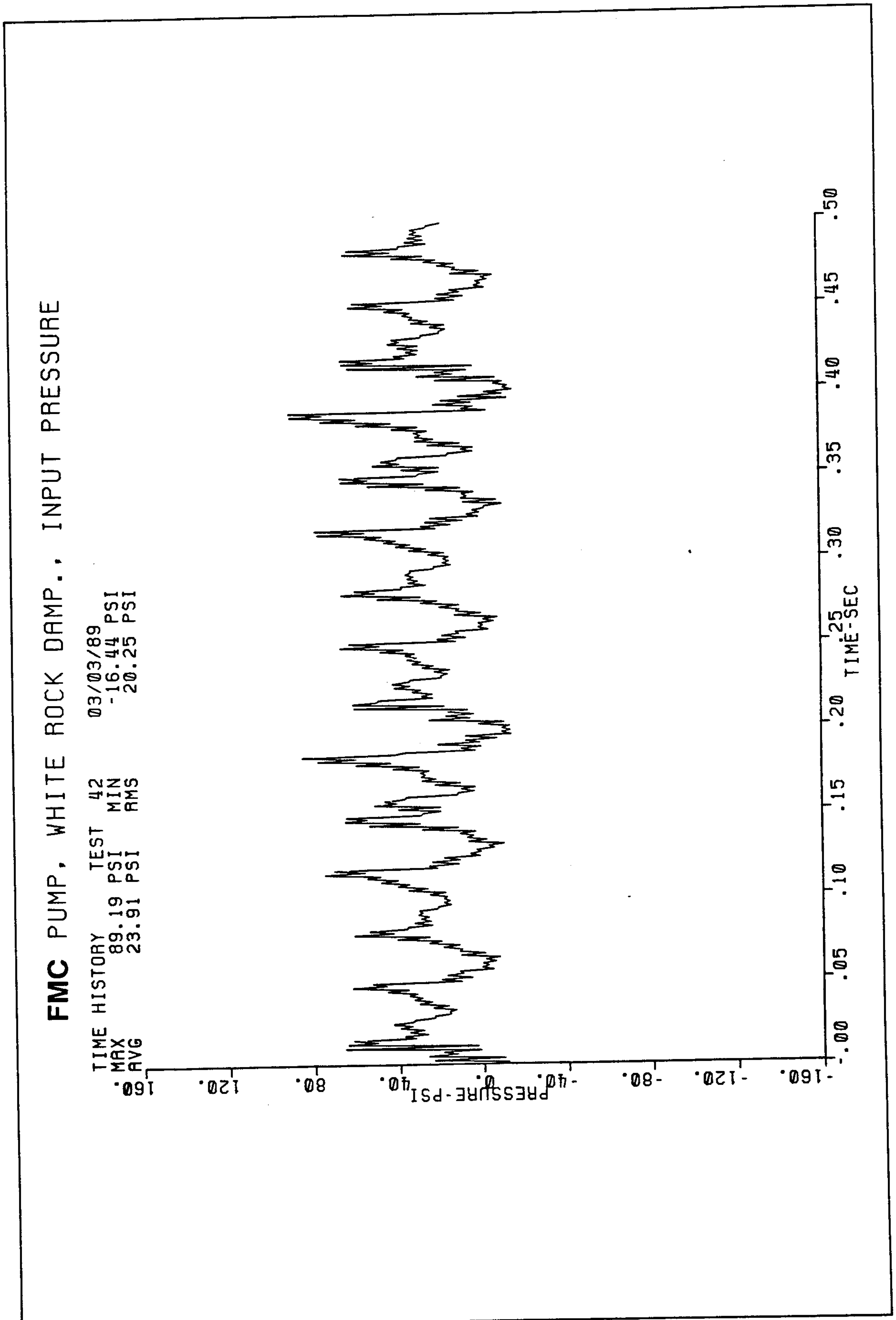

FMC PUMP, YOUNG DAMP., V. ACCEL. PUMP
TIME HISTORY TEST 45 03/06/89
MAX 12.92 G'S MIN -13.95 G'S
AVG -0.22 G'S RMS 1.46 G'S
TIME-SEC
ACCELERATION-G'S
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
16. 12. 8.0 4.0 0.0 -4.0 -8.0 -12.0 -16.0

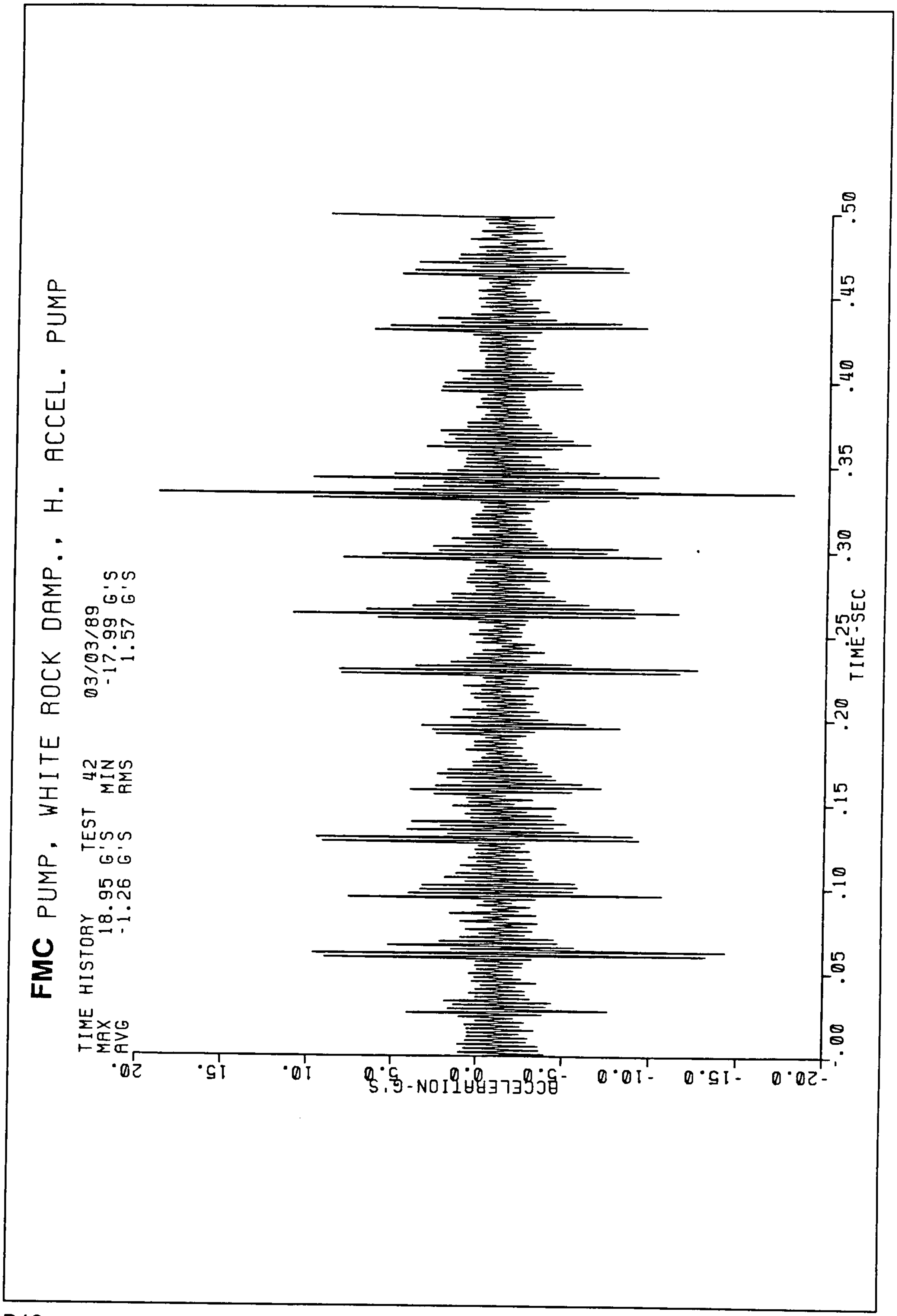

FMC PUMP, YOUNG DAMP., H. ACCEL. FL.
TIME HISTORY TEST 45 03/06/89
MAX 328.32 G'S MIN -306.32 G'S
AVG 20.49 G'S RMS 27.24 G'S
TIME-SEC
ACCELERATION-G'S
X10¹
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
40. 30. 20. 10. 0. -10. -20. -30. -40.

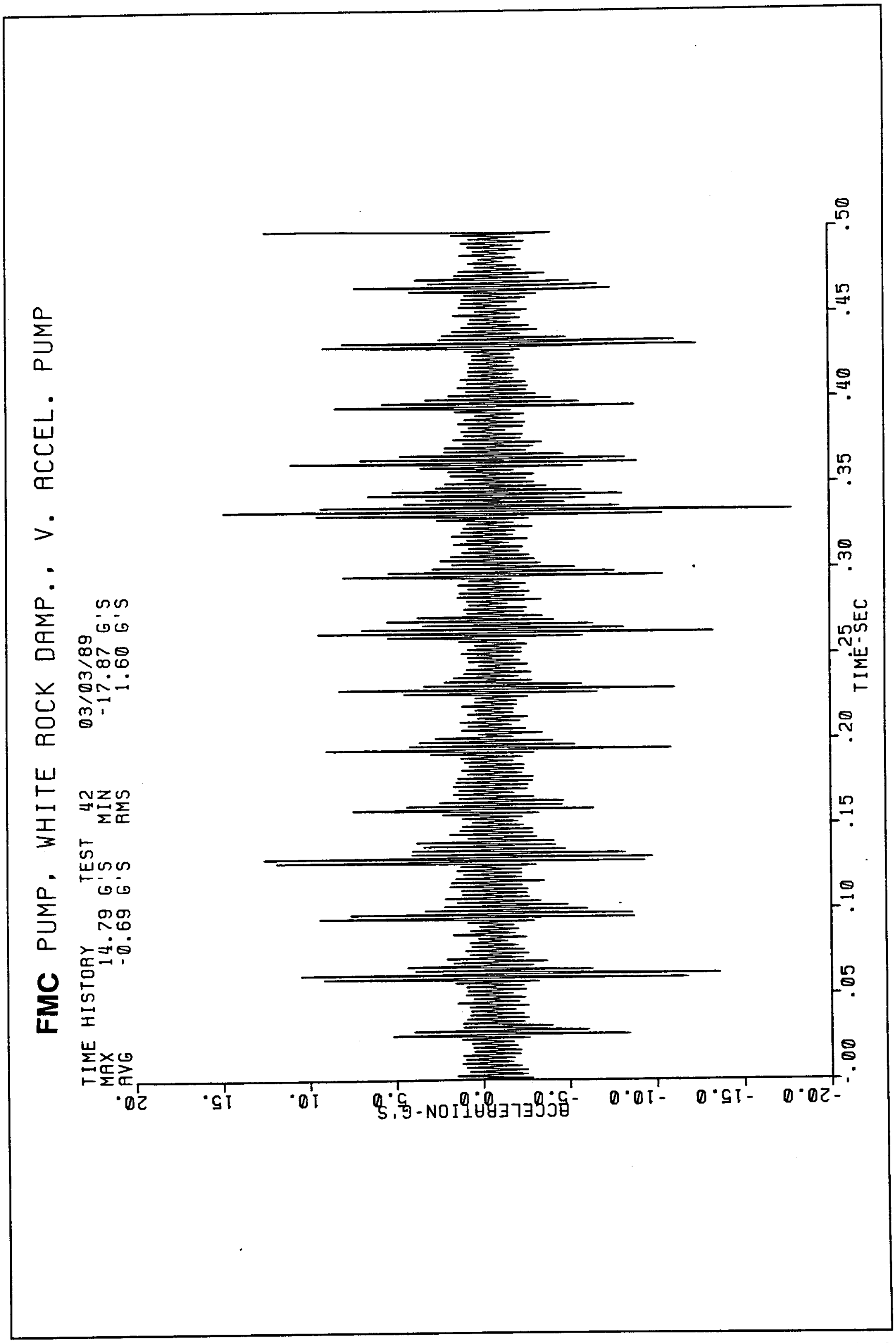

FMC PUMP, YOUNG DAMP., V. ACCEL. FL.
TIME HISTORY TEST 45 03/06/89
MAX 1.11 G'S MIN -1.05 G'S
AVG 0.01 G'S RMS 0.08 G'S
ACCELERATION-G'S
1.6
1.2
.8
.4
0
-.4
-.8
-1.2
-1.6
TIME-SEC
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50

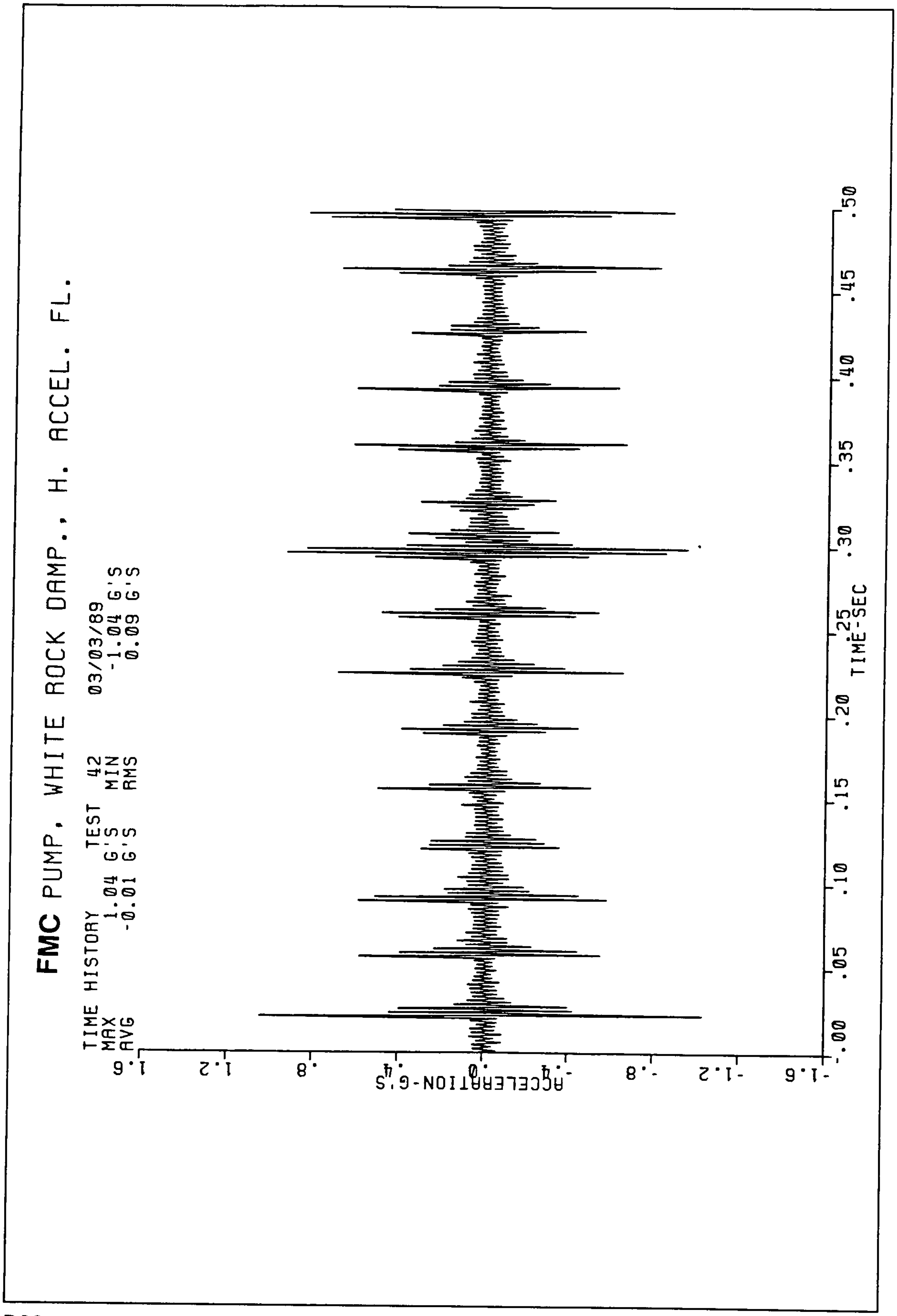
White Rock Pulsation Dampener


FMC PUMP, WHITE ROCK DAMP., OUTPUT PRESSURE
TIME HISTORY TEST 42 03/03/89
MAX 1115.28 PSI MIN 1036.41 PSI
AVG 1080.23 PSI RMS 8.58 PSI
.00
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
TIME-SEC
0.
20.
40.
60.
80.
100.
120.
140.
160.
X10^1
PRESSURE-PSI

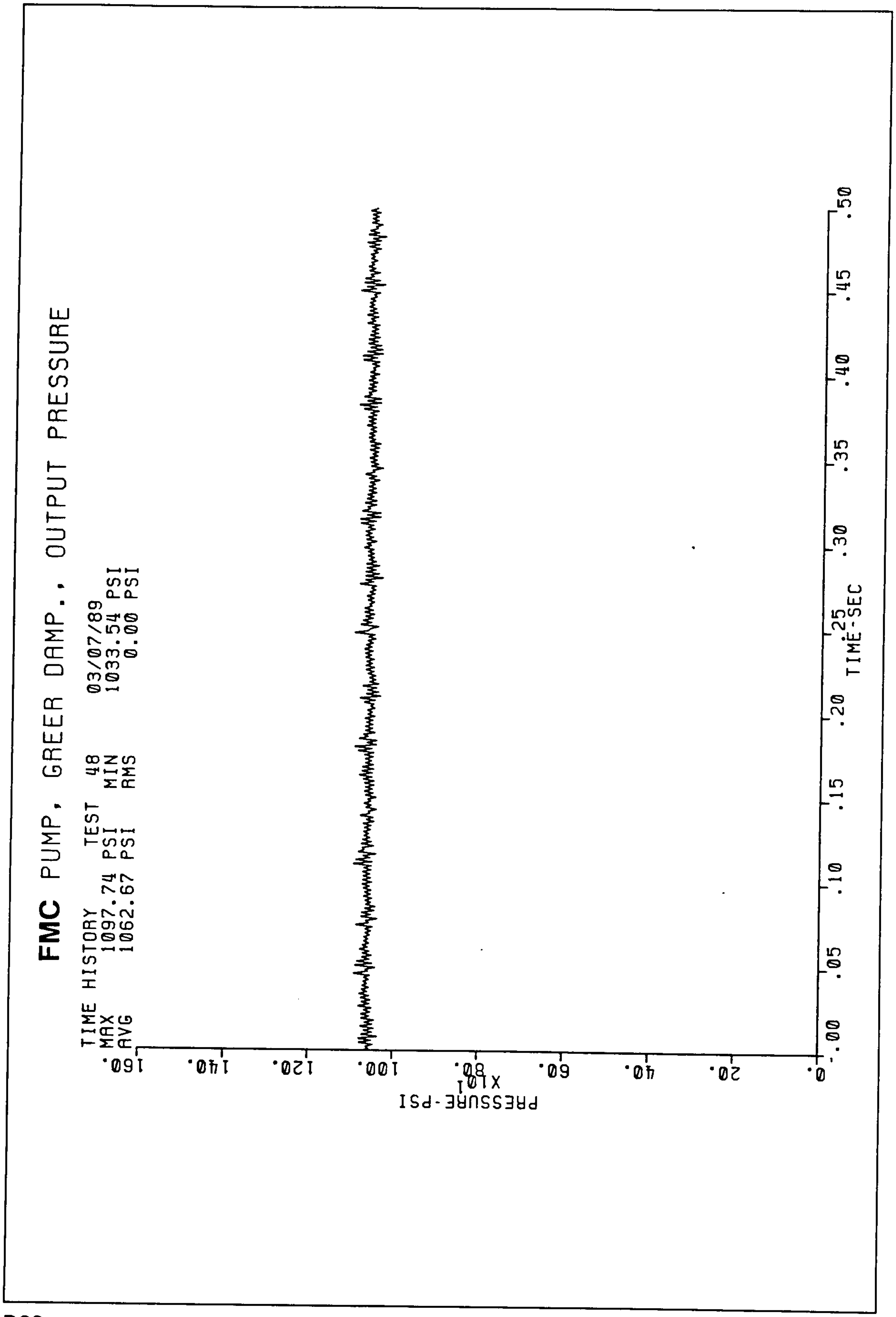

FMC PUMP, WHITE ROCK DAMP., INPUT PRESSURE
TIME HISTORY TEST 42 03/03/89
MAX 89.19 PSI MIN -16.44 PSI
AVG 23.91 PSI RMS 20.25 PSI
PRESSURE-PSI
160. 120. 80. 40. 0. -40. -80. -120. -160.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

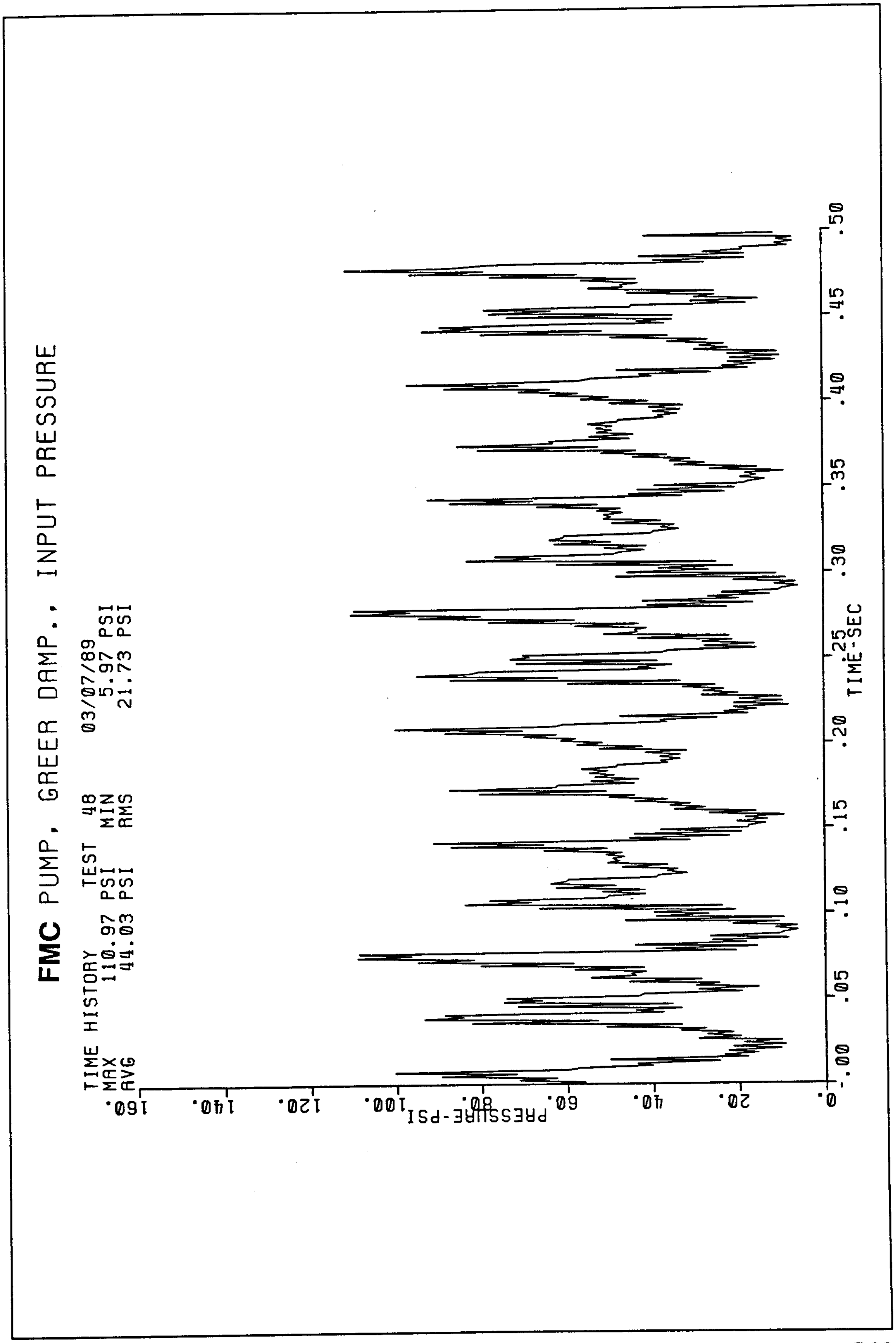

FMC PUMP, WHITE ROCK DAMP., H. ACCEL. PUMP
TIME HISTORY TEST 42 03/03/89
MAX 18.95 G'S MIN -17.99 G'S
AVG -1.26 G'S RMS 1.57 G'S
ACCELERATION-G'S
TIME-SEC

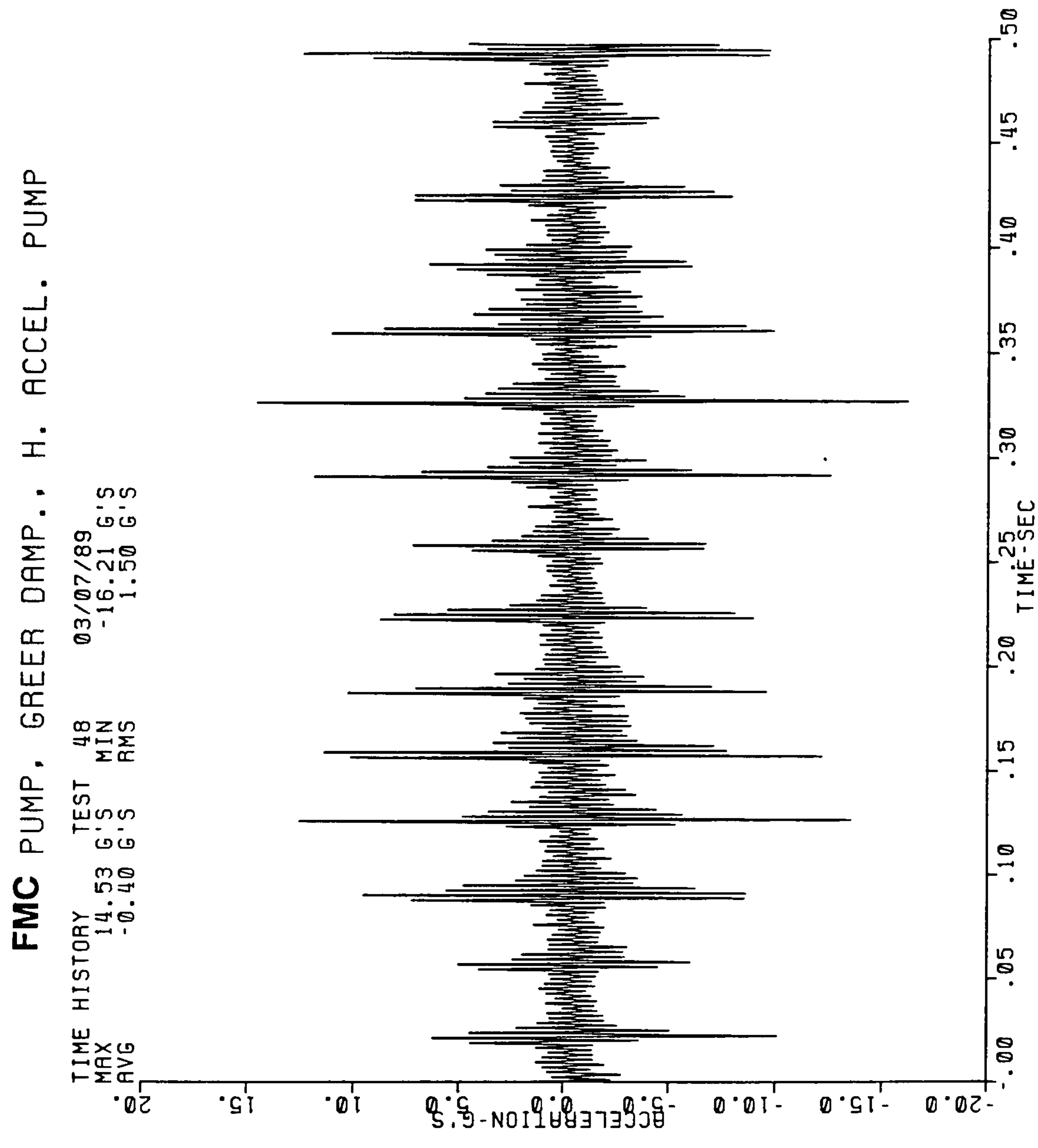

FMC PUMP, WHITE ROCK DAMP., V. ACCEL. PUMP
TIME HISTORY TEST 42 03/03/89
MAX 14.79 G'S MIN -17.87 G'S
AVG -0.69 G'S RMS 1.60 G'S
ACCELERATION-G'S
20. 15. 10. 5.0 0.0 -5.0 -10.0 -15.0 -20.0
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50

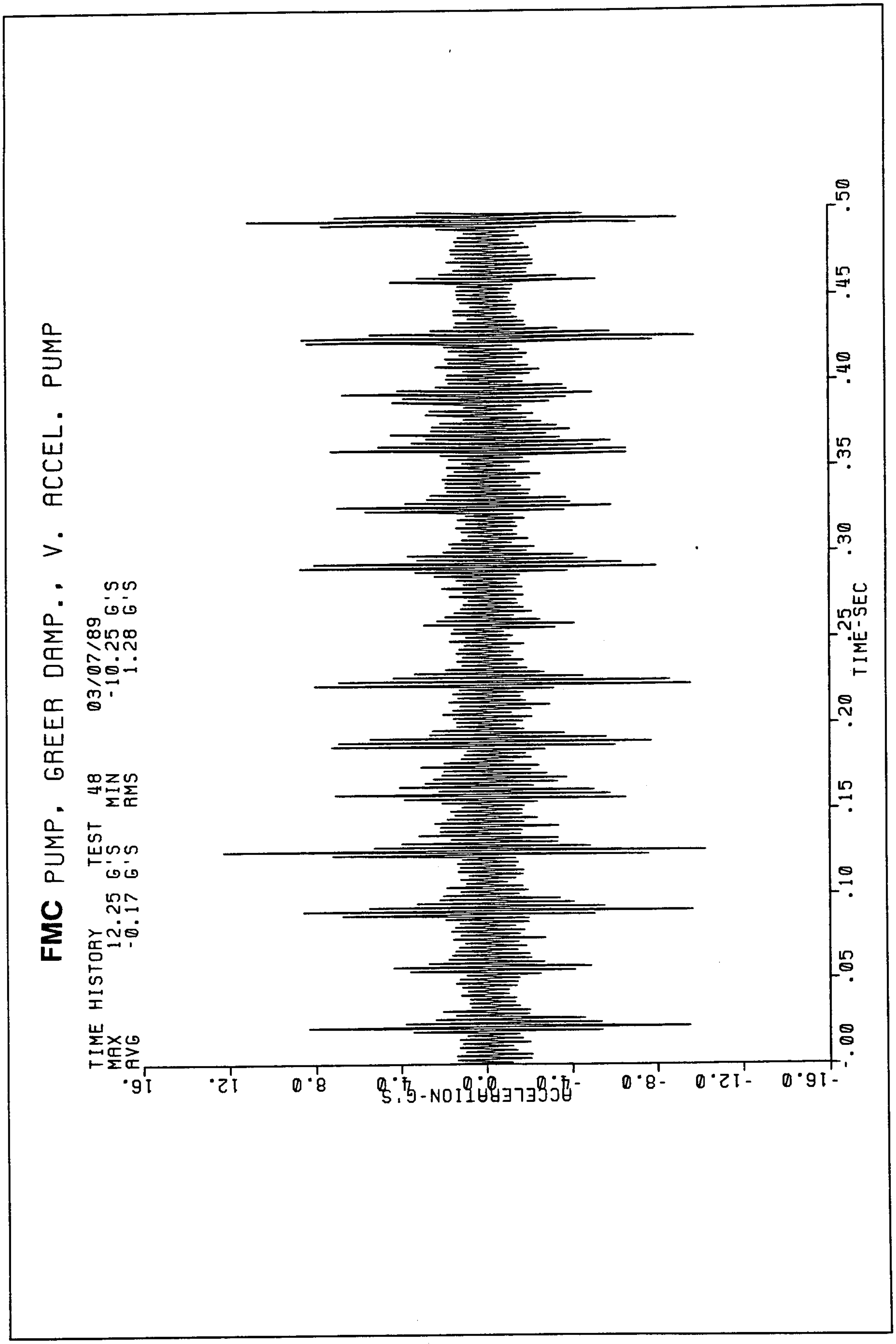

FMC PUMP, WHITE ROCK DAMP., H. ACCEL. FL.
TIME HISTORY TEST 42 03/03/89
MAX 1.04 G'S MIN -1.04 G'S
AVG -0.01 G'S RMS 0.09 G'S
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50
TIME-SEC
1.6 1.2 .8 .4 0 -.4 -.8 -1.2 -1.6
ACCELERATION-G'S

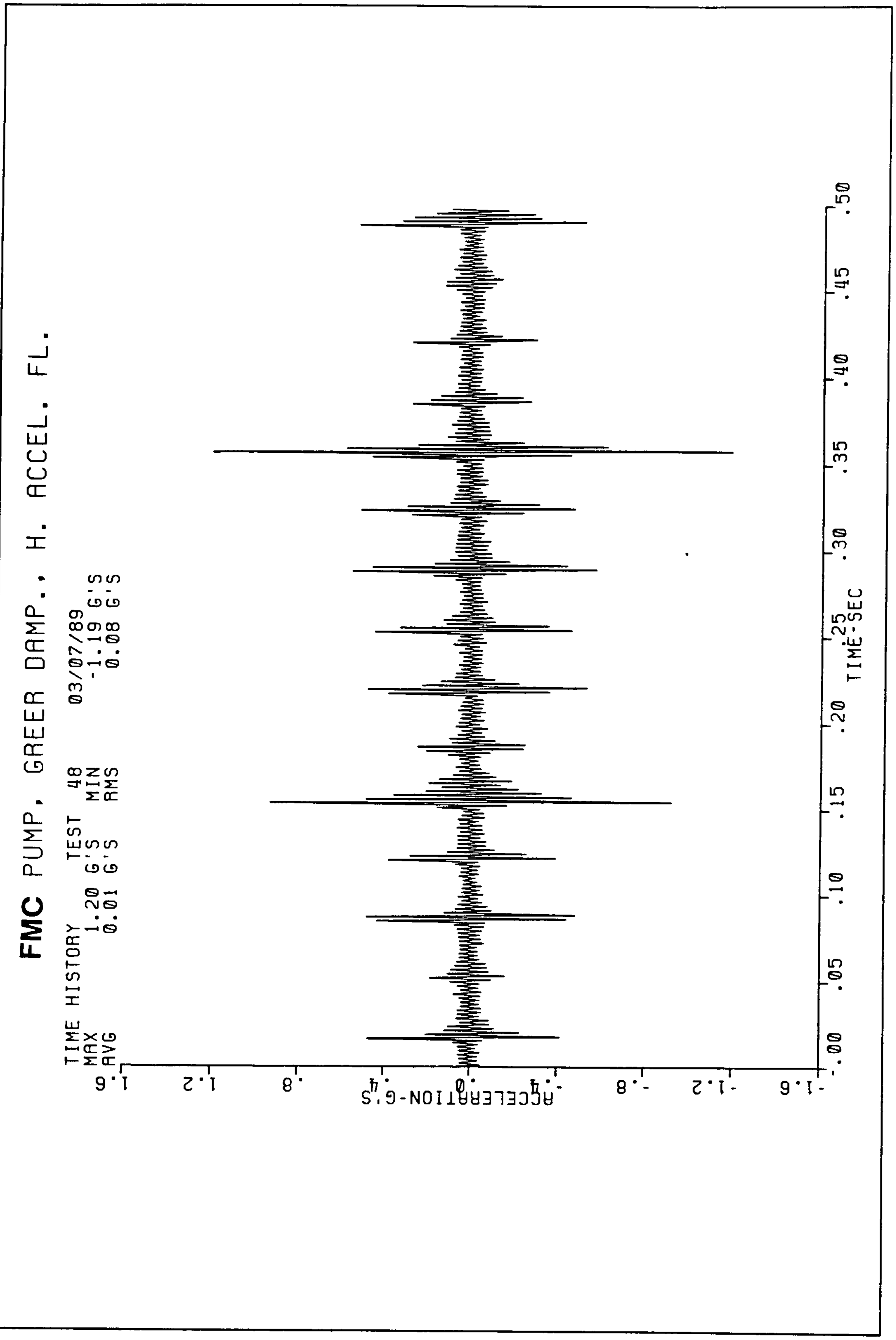
Greer 1-Gal (4-Qt) Pulsation Dampener


FMC PUMP, GREER DAMP., OUTPUT PRESSURE
TIME HISTORY TEST 48 03/07/89
MAX 1097.74 PSI MIN 1033.54 PSI
AVG 1062.67 PSI RMS 0.00 PSI
PRESSURE-PSI
X10¹
0. 20. 40. 60. 80. 100. 120. 140. 160.
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


FMC PUMP, GREER DAMP., INPUT PRESSURE
TIME HISTORY TEST 48 03/07/89
MAX 110.97 PSI MIN 5.97 PSI
AVG 44.03 PSI RMS 21.73 PSI
PRESSURE-PSI
0. 20. 40. 60. 80. 100. 120. 140. 160.
TIME-SEC
-.00 .00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


FMC PUMP, GREER DAMP., H. ACCEL. PUMP
TIME HISTORY TEST 48 03/07/89
MAX 14.53 G'S MIN -16.21 G'S
AVG -0.40 G'S RMS 1.50 G'S
TIME-SEC
ACCELERATION-G'S


FMC PUMP, GREER DAMP., V. ACCEL. PUMP
TIME HISTORY TEST 48 03/07/89
MAX 12.25 G'S MIN -10.25 G'S
AVG -0.17 G'S RMS 1.28 G'S
ACCELERATION-G'S
16. 12. 8.0 4.0 0.0 -4.0 -8.0 -12.0 -16.0
TIME-SEC
.00 .05 .10 .15 .20 .25 .30 .35 .40 .45 .50


FMC PUMP, GREER DAMP., H. ACCEL. FL.
TIME HISTORY TEST 48 03/07/89
MAX 1.20 G'S MIN -1.19 G'S
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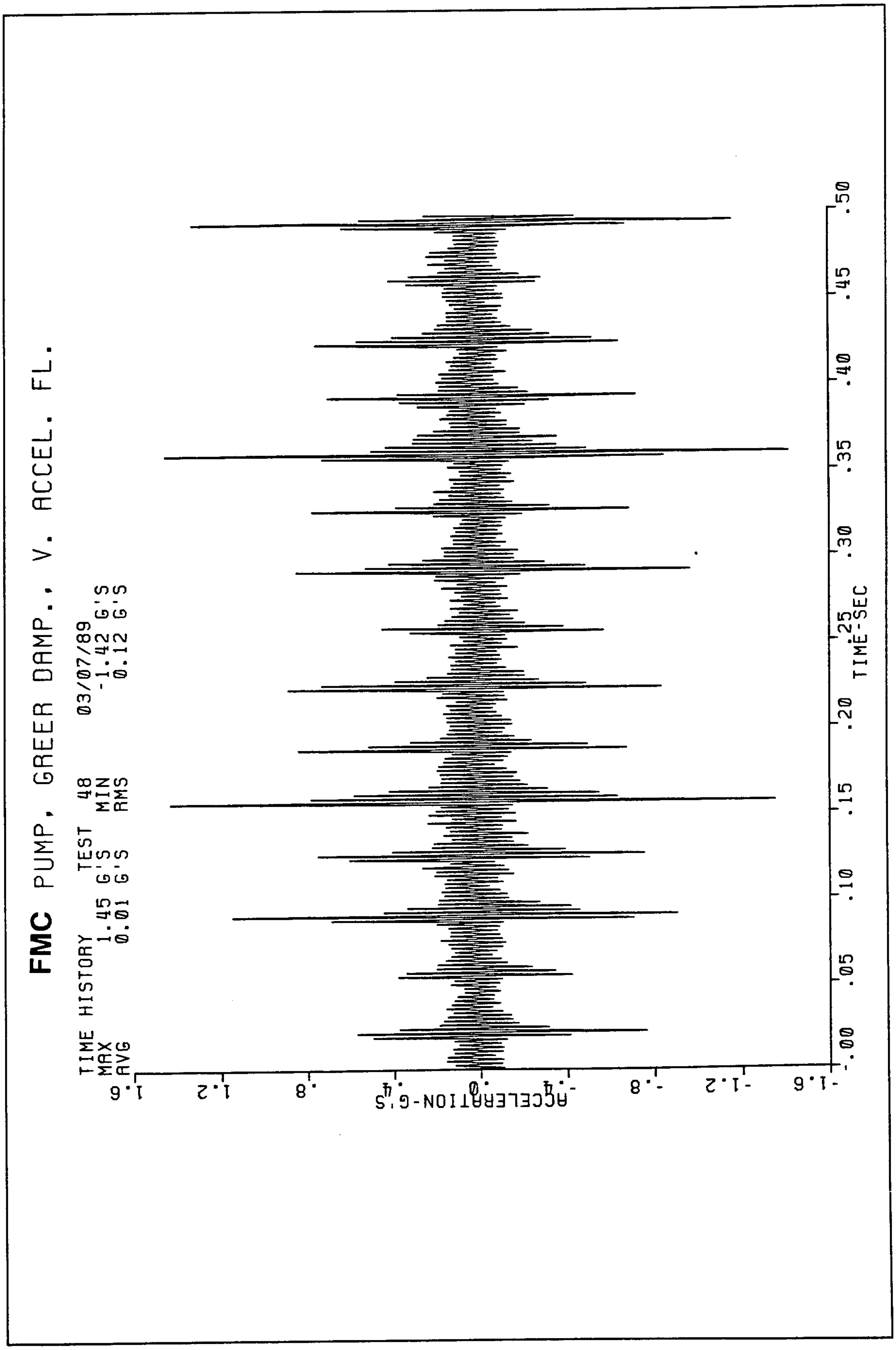
TIME-SEC
ACCELERATION-G'S


FMC PUMP, GREER DAMP., V. ACCEL. FL.
TIME HISTORY TEST 48 03/07/89
MAX 1.45 G'S MIN -1.42 G'S
AVG 0.01 G'S RMS 0.12 G'S
TIME-SEC
ACCELERATION-G'S

Appendix E
Copper-Nickel Test Results

EDX unit. Scanning electron microscope (SEM) micrographs of inner pipe wall features were produced, elemental composition of deposits on the surface were identified, depth of pitting was determined, and a high resolution X-ray map showing distribution and concentration of elements was created.

The untested straight pipe shows preexisting voids and grain boundaries (Figures E1 and E2), while the untested elbow shows similar features and striations likely to have resulted from the bending process (Figures E3, E4, and E5). Preexisting voids were generally less than 25 µm long and less than 5 µm wide. Some spherical voids were present ranging from 2 µm, to less than 1 µm in diameter. The voids in the elbow appear to be stretched in the long-axis direction of the pipe. Grains were approximately 5 µm in size. Surface debris associated with the grain boundaries range from 0.1 to 0.8 µm in diameter (Figure E2).

Surface debris (scalelike material) was evident on the inside surface of the tested pipes (Figures E6 and E7). Large pits were also observed (Figures E8 and E9). These large pits were typically less than 200 µm in diameter. Pits were commonly 0.5 µm in diameter and believed to have similar depths as diameter. Figures E10 and E11 show the inside surface of the straight pipe and elbow, respectively, after the scale was removed.

Elemental analysis of untested pipe (Figure E2) using EDX indicated that copper (Cu) and Nickel (Ni) were the major elements present. Iron (Fe), manganese (Mn), oxygen (O), and carbon (C) were present as trace elements (Figure E12). EDX data collected from the untested elbow shown in Figure E5 indicate the same chemistry as that of the untested straight pipe (Figure E13). The spectrum shows chemistry similar to what was collected from scale in the elbow. Aluminum (Al), magnesium (Mg), silicon (Si), sulfur (S), chlorine (Cl), sodium (Na), zinc (Zn), oxygen (O), and carbon (C) were present.

High resolution X-ray maps were made of tested pipes. Figures E14, E15, and E16 are hard copies of X-ray maps made from the inside surface of the elbow. The area was partially coated with the scale material. Figure E14

shows the distribution of copper, Figure E15 shows the distribution of nickel, and Figure E16 the distribution of chloride.

Based on the SEM and EDX findings, the following conclusions can be made:

The small particles shown in Figures E2 and E5 may be a copper/nickel oxide that has formed over the surface.

Small pits have formed in the surface of the used pipe. The depths of the pits found in the elbow are 25 to 50 µm. Pits of this size do not pose a significant structural threat to the integrity of the pipe. Extrapolation of pit growth to yield a useful life approximation based on the known information is not warranted.

The X-ray maps of Cu, Ni, and Cl show Cu to be common throughout the pipe. The map of Ni parallels that of the Cl map (Figure E16), suggesting the Cl is now a Cu/Cl phase.

The other elements detected in trace amounts are associated with the added salt and potable drinking water comprising the test fluid.

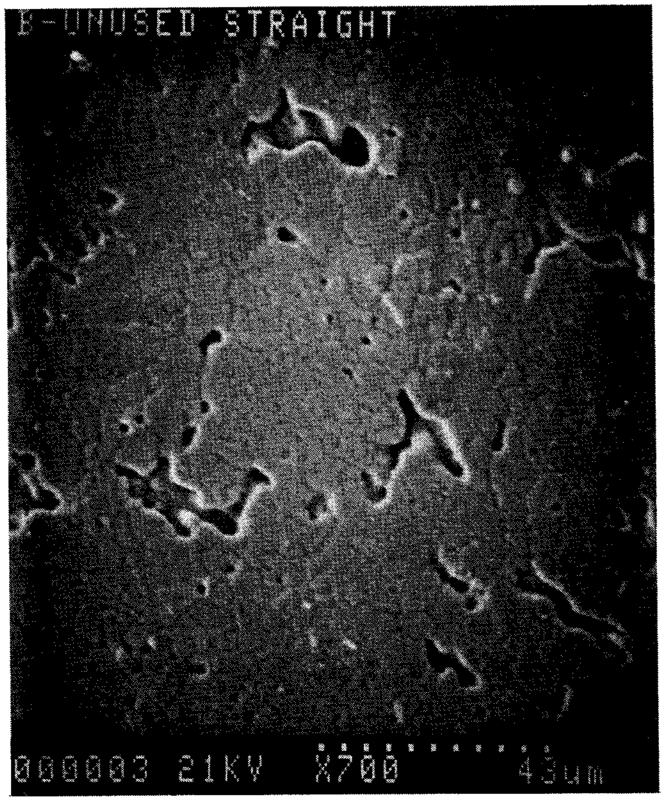


Figure E1. X700. Irregular voids were common to inside surface of pipe. "Mosaic" design can be seen on pipe surface

Figure E2. X5,000. Round voids like those seen in photomicrograph were also quite common. Small particles on surface are probably Cu/Ni oxides

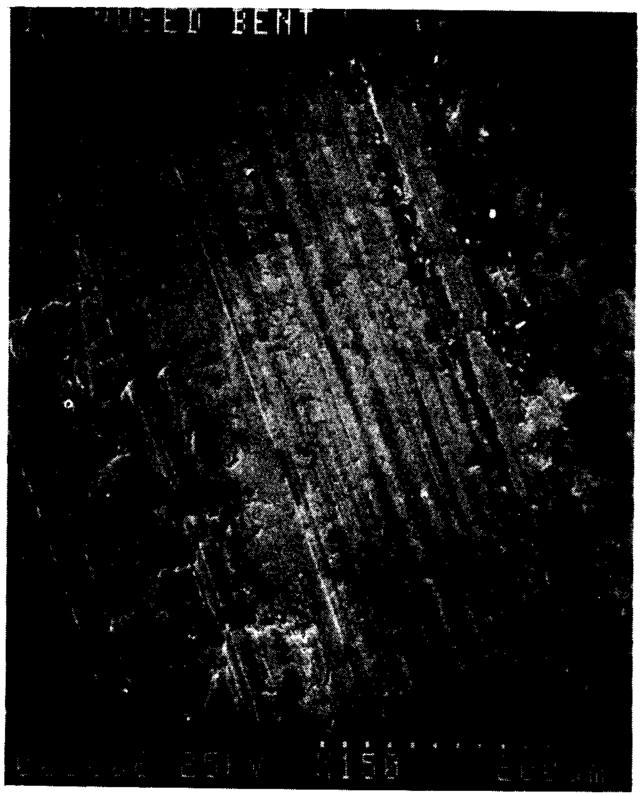


Figure E3. X150. Inside surface of elbow was striated

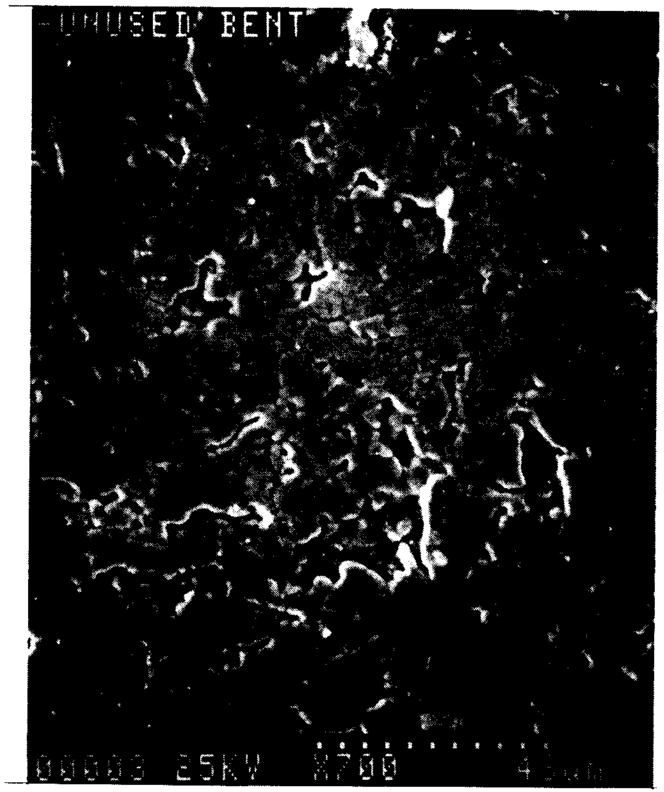


Figure E4. X700. Micrograph of untested elbow shows same "mosaic" design and irregular voids present in straight pipe

Figure E5. X2,500. Higher magnification showing “mosaic” design in elbow. Voids in elbow appear to be stretched in direction of long axis

Figure E6. X100. “Scale” collected on inside surface of tested pipe. Clear looking surface in center contains pits. Figure E13 shows chemistry of scale

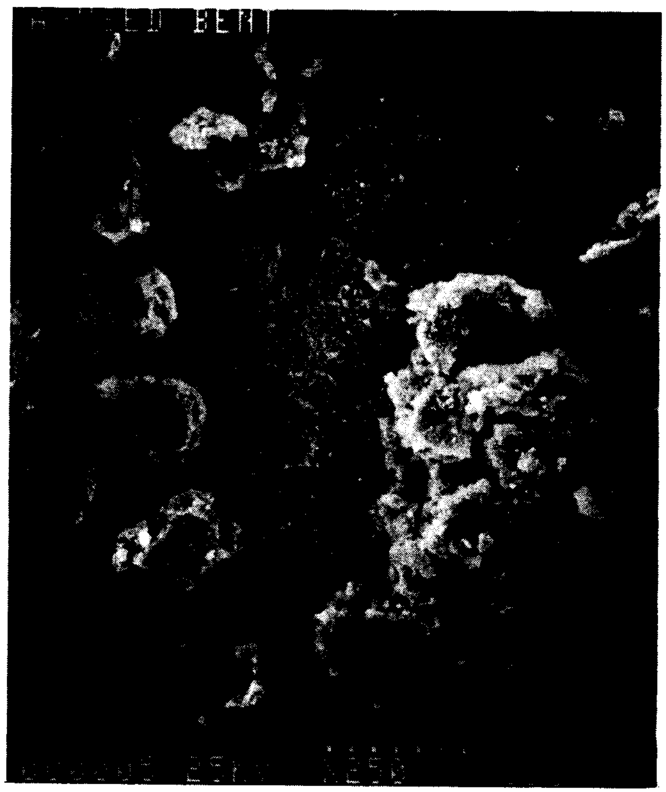


Figure E7. X250. Shows deposits inside elbow. Surface of pipe is also shown. Much of original surface is gone

Figure E8. X220. View is typical of larger pits. Note that smaller pit is inside larger pit

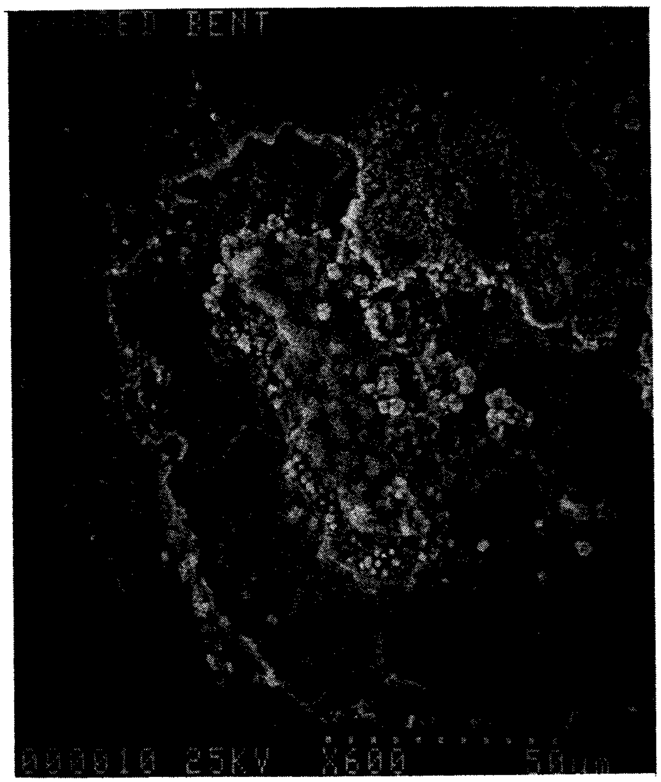


Figure E9. X600. Several large pits were found on inside surface of elbow. This one is about 150 by 100 µm in size

Figure E10. X3,000. Shows damage in straight pipe caused by saline solution. Pits average approximately 0.5 µm in diameter. "Valleys" that create boundaries for mosaic design have been deepened, and pits are in valleys

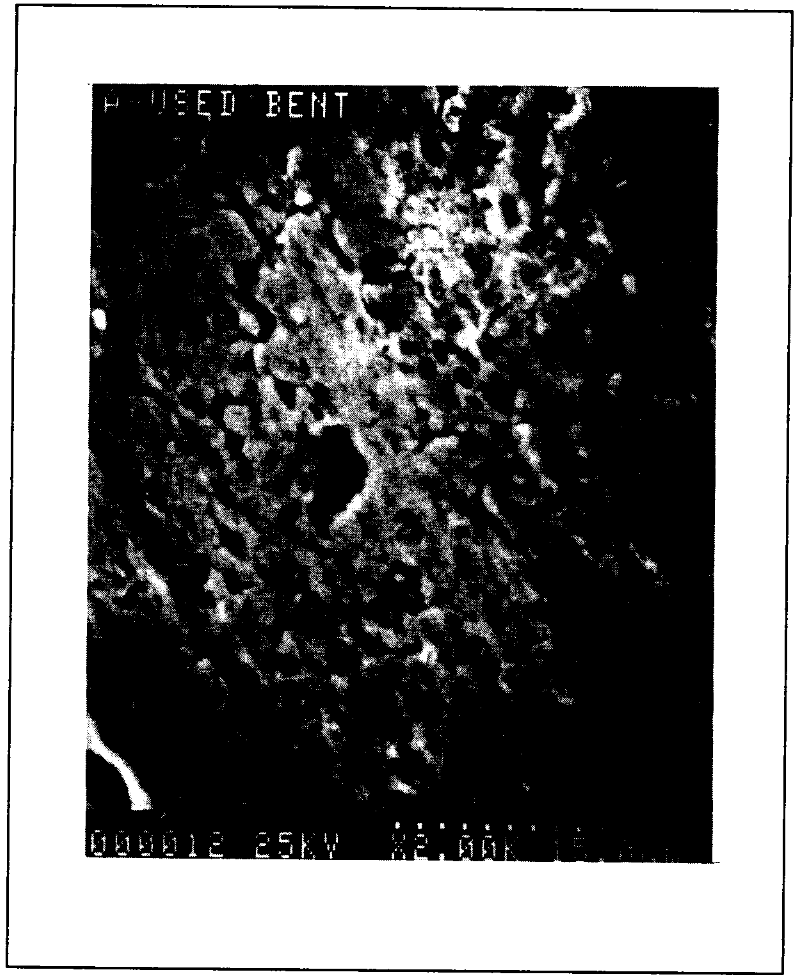


Figure E11. X2,000. Shows damage done to elbow. Pits are larger in elbow area than they were in straight pipe

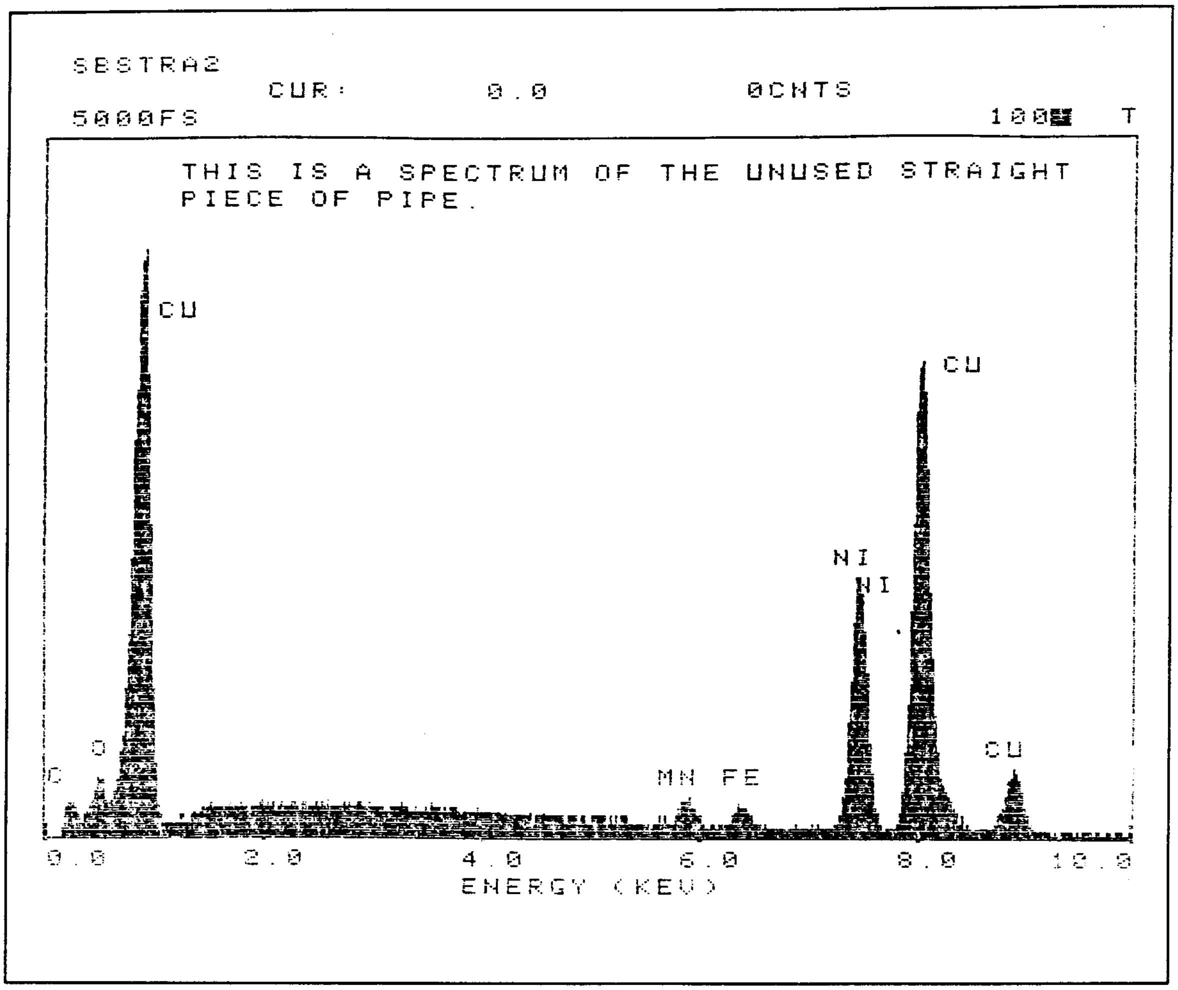


Figure E12. Spectrum of unused straight piece of pipe

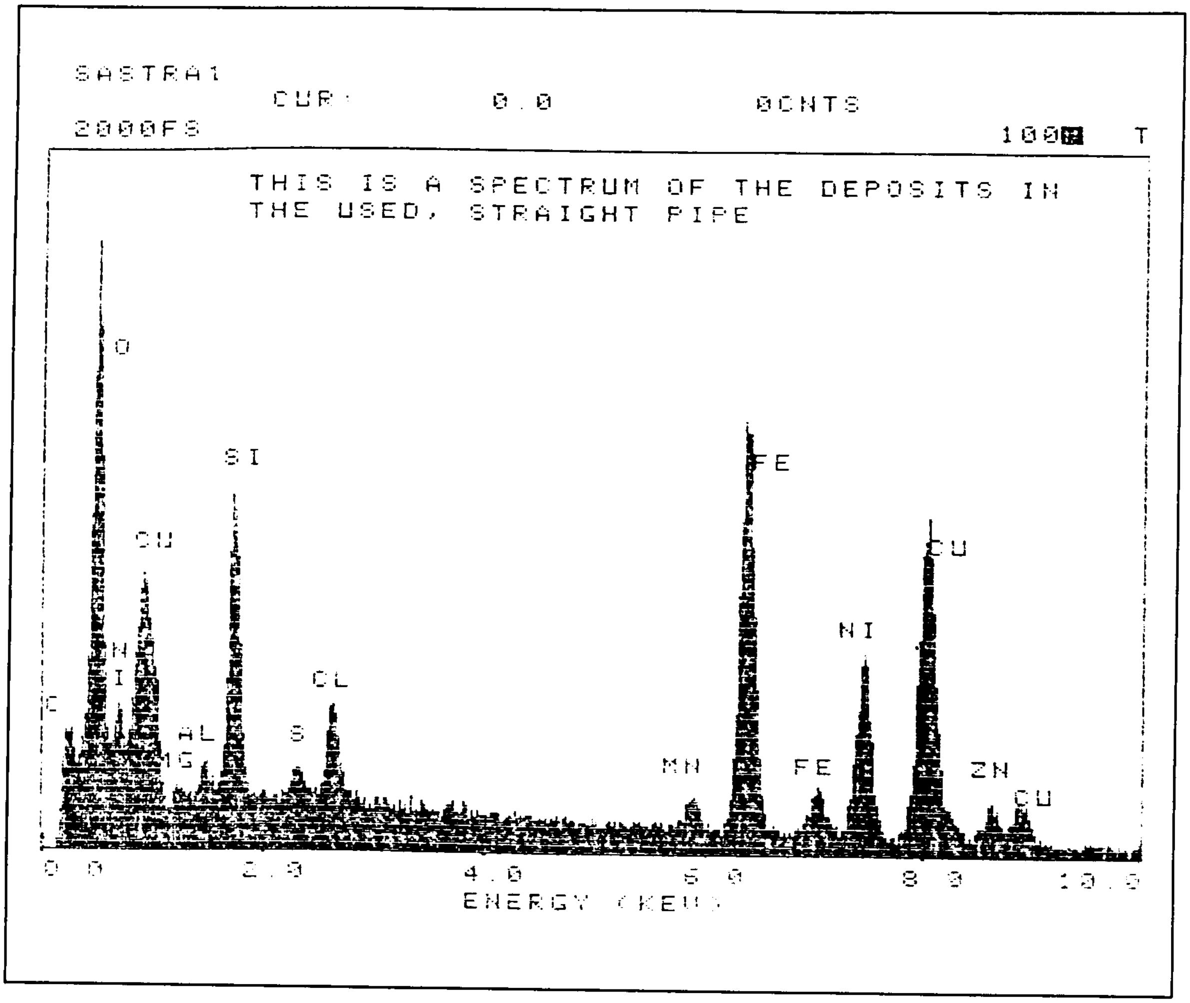


Figure E13. Spectrum of deposits in used straight pipe

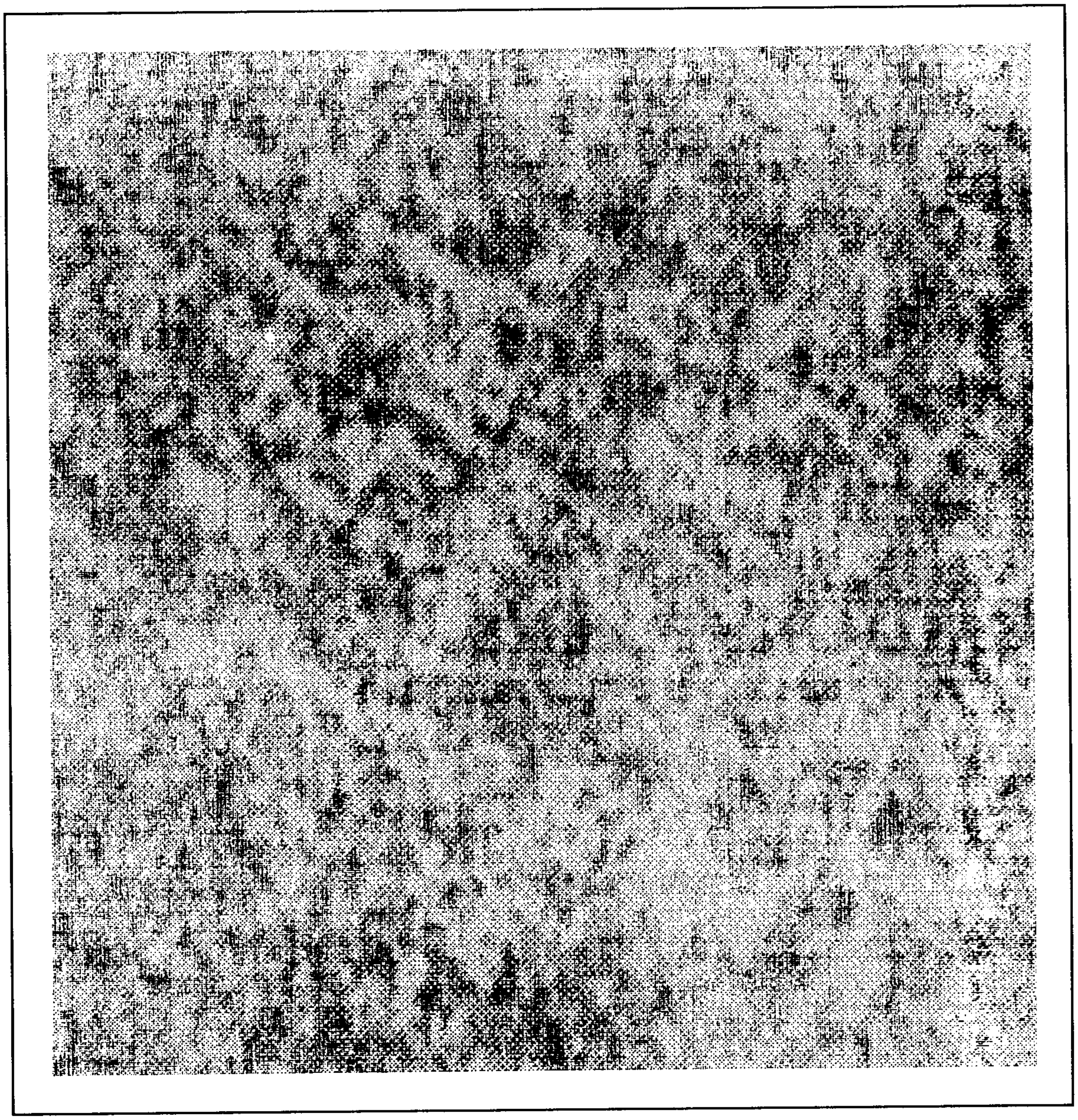


Figure E14. EDX high resolution X-ray map for copper in a tested pipe. Light areas show homogeneous distribution of copper in sample

Figure E15. EDX high resolution X-ray map showing distribution of nickel. Light areas indicate concentrations of nickel in some areas

Figure E16. EDX high resolution X-ray map of chlorine. Orientation of concentration of chlorine is similar to that of nickel shown in previous figure

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Wayne W. Sharp, Charles R. O'Quinn, Michael G. Channell

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13. ABSTRACT *(Maximum 200 words)*

Mobile reverse osmosis water purification units (ROWPUs) are used by the Army for production of potable water from saline, brackish, and freshwater sources. The reverse osmosis is a membrane process that requires a high pressure feed stream; therefore, a high pressure pump is a key component of the ROWPU.

This report provides data collected from a unified testing program applicable to all high pressure pumping units that have potential use as ROWPU components. The testing program consists of three phases (initial inspection, start-up testing, and endurance testing). All pumping units evaluated during this testing were subjected to the three test phases.

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